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EDITORIAL

PARTICIPATION OF THE U.K. IN SPACE FLIGHT DEVELOPMENT— EUROPEAN COLLABORATION

The cancellation of Blue Streak as a military project completely changes the situation with respect to a U.K. participation in the future development of space exploration.

It is important that the work on Blue Streak and its ancillary developments should not be discontinued. Such an action would serve no useful economic purpose. Large departments in a number of our major industrial organisations are heavily committed to this project and it is doubtful if the highly specialised effort involved could be usefully or effectively redeployed except over a long period. Nothing can be lost in maintaining the present effort for the purpose of building up a future civil space programme. The alternative of suddenly stopping all this work might save money on paper but it would not add, effectively, to the nation's prosperity. On the contrary, it might produce redundancy and some hardship.

The important question that should be asked is not whether Britain should keep out of the field in view of the magnitude of this expenditure, but rather should this country attempt to proceed alone. Serious consideration should be given to the possibility of entering into a joint programme with other countries in order to spread the load both in terms of finance and industrial and scientific effort. The obvious partners in such an enterprise would be our sister nations in Europe, e.g. the O.E.E.C. countries, and Australia. There exists already a number of such co-operative projects in nuclear science and engineering which are functioning in a most effective manner.

We should recognise this from the start and think in terms of a European space project rather than a U.K. programme. The importance of doing this lies in the fact that, in terms of industrial and scientific resources, Europe can cope on equal terms with the U.S.A. and U.S.S.R.

The U.K. could place at the disposal of a European Project existing facilities and the background of work on Blue Streak and, thereafter, contribute a reasonable proportion of the annual budget for the joint programme. In the early stages of the work the U.K. could also manufacture Black Knight and Skylark rockets for a joint upper atmosphere and space research programme, the cost of the vehicles and operations being shared in an appropriate manner.

It is expected that, in such a European programme, Australia would be asked to participate in view of the special facilities possessed by that country and other non-European nations which are not committed to major space projects might also be invited to participate.

It is important to realise that joint-European projects are already functioning effectively along the above lines and there is no reason why the principles should not be extended successfully to space flight.

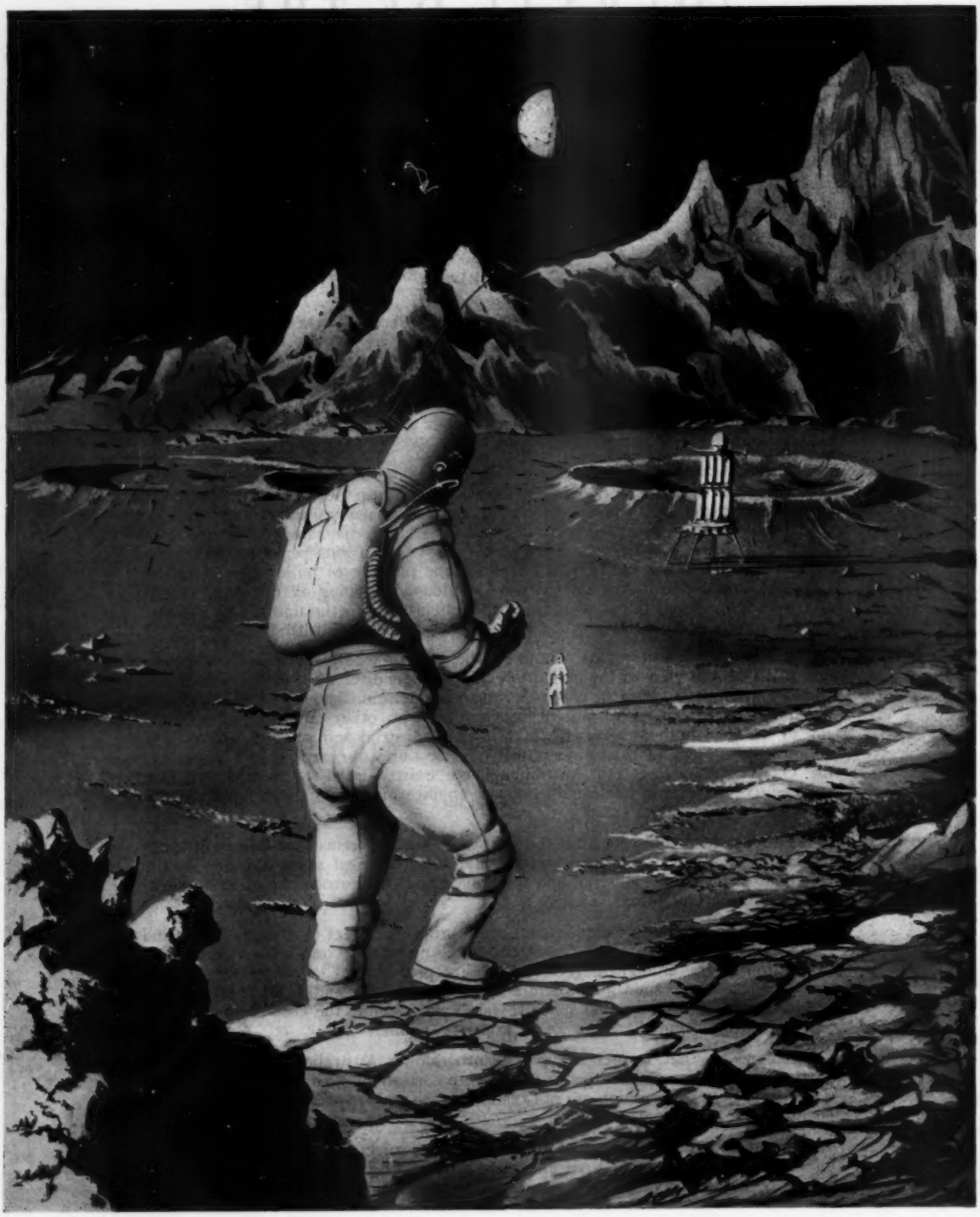


Fig. 1. The aim—Man on the Moon.

HIGH ALTITUDE CHAMBERS AND PRESSURE SUITS AND THEIR PART IN MANNED FLIGHT TO THE MOON*

By E. W. Still,† Ph.D., B Sc., A.C.G.I., A.M.I.Mech.E., F.R.Ae.S., F.B.I.S.

ABSTRACT

This paper attempts to reduce to basic facts the environmental system engineering to sustain man during all phases of a journey to the Moon and back. It reviews current and projected man-bearing vehicles. Information from these projects is then used to estimate parameters such as size of cabin, number of crew, duration of flight, and possible heat loads for all stages of such a journey. This is followed by a description of the environmental requirements necessary to sustain life, together with a statement of assumptions in respect of the flight phases concerned.

The main part of the paper describes in detail the environmental engineering systems for a small Earth-to-orbit vehicle, a large space station, and a lunar suit. In addition, mention is made of some possible emergencies and their counter-measures.

The conclusion is reached that the environmental engineering for a manned trip to the moon presents no insuperable extension of existing knowledge, but if voyages are projected to Mars or other planets, this will require considerable development of closed-circuit ecology.

INTRODUCTION

This paper was first suggested some two years ago but the author evaded the issue, being somewhat sceptical of the whole idea of manned flight into Space. Events of the last two years have indicated the need to revise this attitude of mind and the more involved the writer has become in preparing this paper, the more obvious is the fact that environmental engineering for such a lunar voyage is quite within the realms of our existing knowledge.

Soviet scientists have already shown that rockets can reach the moon so that what has, until now, been considered as science fiction, has suddenly become fact. However, information in many more fields will be required and much theoretical knowledge reduced to hard engineering facts before a manned lunar landing is made.

The purpose of this paper is to suggest detailed proposals for the air conditioning, pressurisation, and oxygen systems in such sealed vehicles.

TABLE I — UNITED STATES PROGRAMME

Project	*Date*
High Altitude Sounding Rockets	1946
'Manhigh' Altitude Balloon Experiments	1957
Instrumented Earth Satellites	1958
X-15 High Altitude Rocket Flights	1959
Thor-Delta Rockets	1960/62
Mercury Manned Earth Orbital Flights	1961
Centaur Rocket/730 lb. payload for a lunar landing	1961/62
Saturn Rocket/1·5 million lb. thrust	1962/63
Dyna-Soar re-entry glider	1963/66
Manned Satellite Development	1963
Nova Rocket/6 million lb. thrust	1965/68
Orbiting Space Station	by 1970
Manned Circumlunar Orbit	by 1970
Manned Lunar Landing	After 1970

A short survey is made of the 'Manhigh', X-15, and Mercury projects of the current space programmes, and continues with the types of vehicle capable of manned space travel.

There would seem to be little doubt of the ability to develop such vehicles. The time table is vague and obviously bears a direct relationship to the amount of money and effort which the various governments are prepared to allot to these projects. It is interesting to note that Lockheed Aircraft Corporation estimate that the cost of their placing a 10-man space-station in orbit would be more than £700,000,000. Table I shows what is believed to be the United States programme.

Whilst the problems connected with the air conditioning of man in a sealed vessel may be understood because there are parallels with existing pressurised aircraft, the problem of weightlessness is one that will probably not be solved until man orbits the earth, since even with the X-15 aircraft the phenomenon will be experienced only for a maximum of five minutes. The Mercury project will achieve, for the first time, this new condition when the vehicle orbits the earth as the final duration of its flight will be about five hours.

The review of existing projects describes in more detail the environmental systems for the 'Manhigh', X-15, and the Mercury vehicles which represent the latest thinking available on pressurisation and oxygen systems for a sealed manned capsule. The review continues, in less detail, with the systems of a series of projects of which the Lockheed Aircraft Corporation proposal has been analysed from the aspect of environmental engineering. The actual cabin dimensions of the re-entry vehicle and the space station together with the heat loads from the electrical systems are used as a basis for the main content of the paper.

* In order to accelerate the publication of this paper the Council has decided to use the original typesetting prepared for issuing preprints at the meeting.—ED.

† Technical Director, Normalair Ltd.

The detailed discussion then covers (*a*) the re-entry vehicle, (*b*) the space station, and (*c*) the lunar suit.

The conclusion is reached that the environmental engineering necessary to sustain man in his journey to and from the Moon, and to enable him to walk freely on its surface, is within the realms of practical engineering rather than science-fiction. The facts also make it clear, however, that a manned trip to Mars or further afield would probably necessitate new methods of providing oxygen and removing carbon dioxide.

In this section a series of environments, each approaching more closely the objective of a man-sustaining environment in free space, is briefly described in connection with the vehicles, actual or projected, which contain or carry them; a start is made with the 'Manhigh II' balloon flight of 1957, itself the successor to many previous high altitude balloon excursions. It is interesting to note that even as late as 1960, a man had stayed at extreme altitude for a longer time by balloon than by any other means, and that the first ascent to 23,000 ft., with the French scientist Gay-Lussac making observations on humidity and terrestrial magnetism, was as long ago as 1804.

'Manhigh II'

The polyethylene balloon for this flight was of three million cubic feet capacity, with a 200 ft. diameter. It weighed 960 lb. and the capsule was 1,700 lb., of which 650 lb. was battery ballast. The capsule was 36 in. in diameter and 89 in. high.[1]

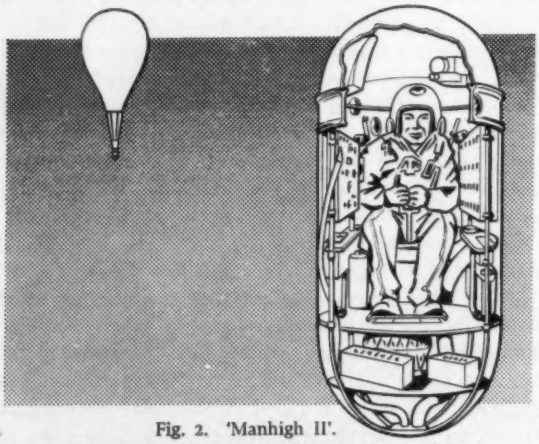


Fig. 2. 'Manhigh II'.
(*With acknowledgement to Winzen Research Inc.*)

The 'Manhigh II' balloon flight was on August the 19th and 20th, 1957; it lasted over 32 hours, and the occupant of the capsule, Major D. Simons, U.S.A.F., reached an altitude of 101,500 feet staying at 101,000 ft. for five hours. In his own words,[2] '. . . . the conditions encountered were physically equivalent to those in a manned satellite in terms of the . . . . ambient pressure, incoming radiation, heat balance and control, and in terms of the emotional reaction towards the overall flight plan. . . . . One very significant factor, that of weightlessness, was missing . . . .'

Conditions were in fact much worse than one would hope to provide in a manned satellite. The aluminium gondola was just large enough to take one seated man and a considerable amount of equipment. See Fig. 2. A pressure of 350 millibars (about 26,000 ft.) was maintained in the capsule, the occupant wearing a partial pressure suit in case of emergency; a ⅔ oxygen, ⅙ nitrogen, ⅙ helium mixture was used, and a Beckman oxygen partial pressure meter enabled a check to be kept on the oxygen concentration. Liquid oxygen was used to give a duration well in excess of 30 hours, and an emergency supply of bottled oxygen was also carried. The carbon dioxide concentration was kept down by anhydrous lithium hydroxide, and the water vapour was absorbed by anhydrous lithium chloride backed up by anhydrous magnesium perchlorate; a 24 volt battery provided power for air circulation. During the night section of the flight the carbon dioxide absorbent, becoming very cold and inefficient, allowed the carbon dioxide concentration to reach 4%; this necessitated breathing pure oxygen from the mask at frequent intervals, even on the level dropping to 3% when day came again. For long periods of space-flight the concentration level would, of course, have to be much lower than this.

An air cooling system was employed using a water-boiler, which was effective only above 85,000 ft., but on the ground before launching, dry ice was packed around the top of the capsule to bring the temperature down. The capsule insulation was such as to keep the interior above freezing point at night using only the 200 watts metabolic and instruments load, an aluminium and paper-honeycomb type of insulator being used. For extra warmth, the occupant could also pull an electrically heated 'thermal suit' around him. However, lack of mobility was a serious factor both in decreasing his comfort and in making the execution of simple tasks more difficult.

X-15

In many ways the North American X-15 is a logical descendant of the various American high-speed research aircraft, both rocket- and jet-propelled, which commenced with the Bell X-1 in 1947. However, there are also substantial differences, for instance the provision of two completely separate sets of altitude control systems; besides a more conventional aerodynamic system for use in the atmosphere, a system of 12 hydrogen-peroxide-fuelled jet nozzles provide stability and control during ballistic flight. This is necessary because of the relatively long periods that can be spent

out of the atmosphere in this aircraft. Total free-flight time, after air-launching at 38,000 ft. at Mach. 0·8, will be about 25 minutes, and maximum range 400 miles. Maximum altitude expected is 500,000 ft., or nearly 100 miles.[3]

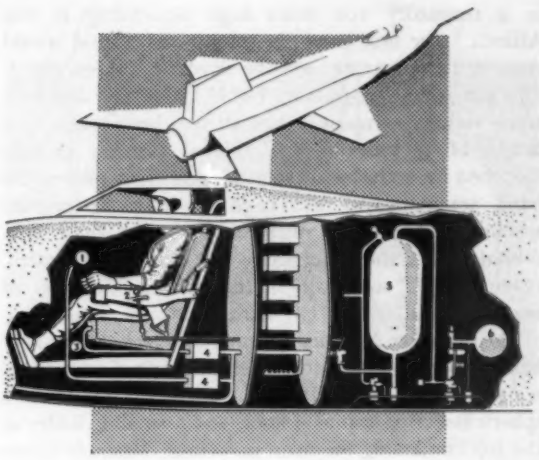
A self-contained pressurisation and cooling system is used, relying on an AiResearch liquid nitrogen storage and feed system. See Fig. 3. The liquid nitrogen, at about −300°F, is forced out of its tank by a flexible expulsion bladder, operated by high pressure helium contained in another small tank.[4] 95% of this nitrogen flow is used for cooling the aircraft nose-cone, operating some pneumatic equipment, cooling and pressurising electronic equipment and rendering inert its environmental atmosphere, and pressurising the pilot's compartment; only 5% is used for pressurising and cooling the pilot's MC-2 full pressure suit. The pilot breathes pure oxygen throughout the trip and the system weighs about 150 lb.[5] Cockpit pressure is only 3·5 lb./sq. in. higher than that outside the aircraft, and to avoid the fire risks attendant on maintaining the whole cockpit at a high (greater than 86%) oxygen level, this system of using two gases, one for pressurisation and one for sustaining life has been adopted.[6]

The MC-2 suit is a lightweight non-rigid garment of nylon fabric with an aluminised outer cover, designed to allow full freedom of movement. It would also be used in an emergency escape, in conjunction with an ejection seat of special design. This latter is required to function at altitudes of up to 120,000 ft., and speeds of up to Mach. 4, and must protect against aerodynamic heating, pressure loss, wind blast and excessive accelerations. It is stabilised in flight by two folding fins and two telescopic booms, and has been tested on high-speed rocket sleds at Edwards Air Force Base, California. The first X-15 captive flight under a B-52 aircraft was made on March 10th, 1959, the first free glide flight on June 8th, and the first powered flight was on September 17th, 1959.

The X-15 will not go into orbit, but will undergo short periods of zero-g flight, during which it is controlled by the jet nozzle system already mentioned above. The aircraft finally lands on a double nose-wheel and two skids, making a 'dead-stick' landing because all main rocket fuel will have been used in the initial flight phase.

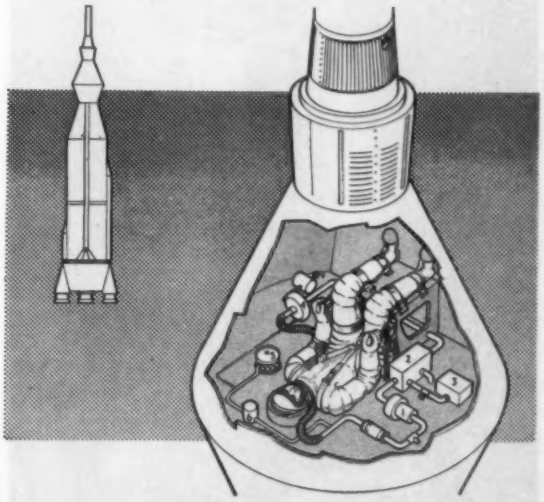
Project Mercury

This vehicle is intended to enable a man to orbit the Earth; it is about the smallest size possible, compatible with this aim, and will be launched by an Atlas rocket. It is hoped to place a man in orbit before the end of 1961, but a great deal of work still lies ahead. The immediate programme is to fire three of these capsules



(1) Cabin Pressurisation and Cooling
(2) System Control
(3) Suit Pressurisation and Cooling
(4) Heat Exchangers
(5) Liquid Nitrogen Storage
(6) High Pressure Helium Storage

Fig. 3. North American X-15.
(By courtesy of the Garrett Corporation of Los Angeles)



(1) Compressor
(2) Evaporator
(3) Water Tank
(4) Water Absorber
(5) Liquid Oxygen
(6) Demand Oxygen Regulator

Fig. 4. Project Mercury.

in a trajectory 100 miles high descending in the Atlantic.[7] The first would be empty, the second would contain a chimpanzee, and the third a man. See Fig. 4. This sub-orbital programme would use Jupiter and Redstone rockets; a monkey has already been taken to a height of 55 miles in a simulated Mercury capsule launched by a cluster of solid rockets. This proved the basic soundness of the re-entry design, parachute system and recovery organisation. After these sub-orbital flights the sequence would then be repeated, culminating if successful in the placing into orbit of one of the seven chosen Astronauts now in training.

The definitive Mercury capsule, of which 20 are now being made by the McDonnell Aircraft Corporation, weighs about a ton. It is a truncated cone with a spherical-section cap as a floor, and a small cylinder at the top containing the main parachute. Mounted above this is an important device, the escape rocket on its tower. This enables the astronaut to blow himself free from the parent rocket, and to descend by parachute in the capsule, at any altitude between ground-level (during take-off) and 100,000 ft. If the escape rocket and tower have not been required by the time this latter altitude is reached, these components are blown free to avoid having to carry them up to orbital altitude.

Fig. 5. Mercury Capsule.
(*By courtesy of Life International*)

A pressure suit is worn by the occupant, who lies on his back on a special couch moulded to his own individual shape, providing support for his body during the high g values experienced during the period up to 'all-burnt' and during re-entry. These accelerative and decelerative forces are both met in the same position, the attitude of the capsule being altered by small rockets during the first stages of re-entry to ensure that the curved floor of the vehicle, which has to bear the brunt of the violent kinetic heating, is facing forwards into the air-stream. Maximum forces of 8 or 9g are expected after take-off and during re-entry, if all goes well. Values of up to 20g might have to be sustained for 8 seconds if the capsule re-entry trajectory were too steep; however, a subject, using the special supporting couch, has shown that even this enormous force can be borne without permanent injury.[7]

The present proposal for dissipating the enormous quantity of heat generated during re-entry, the critical phase of which lasts for five minutes, is to use an 'ablation shield' on the outer surface of the curved floor of the capsule; that is, a layer of laminated glass-resin is allowed to become so hot that it vaporises and absorbs most of the heat that cannot be radiated. This has already been tried with a prototype Mercury capsule, and the temperature inside rose to 150°F for less than a minute, despite the fact that the re-entry trajectory was steeper than planned. Thus, both the heating and deceleration problems seem to be well on the way towards solution as far as Project Mercury is concerned.

The maximum time in orbit would probably be only a few hours, enabling three or four circuits of the Earth to be made before re-entry and descending as close to a previously chosen area of the Atlantic as possible.

The environmental control display indicates cabin temperature and pressure, and the partial pressures of oxygen and carbon dioxide. The environmental control system comprises two loops, the 'cabin circuit' and the 'suit circuit'. The former is responsible for cabin cooling, and for maintaining pressure at 5 lb./sq. in.; the latter cools the suit air, removes odours, carbon dioxide and water vapour, and replenishes oxygen. The pilot breathes pure oxygen at 5 lb./sq. in. and his suit is only inflated if the cabin pressure should drop below that pressure. Activated charcoal removes odours, whilst lithium hydroxide is used for reducing the carbon dioxide concentration. Water vapour is condensed out in a heat

exchanger and trapped in a vinyl sponge, which is periodically squeezed into a condensate container.[8]

Blue Streak/Black Knight Proposal

Whilst the British Government has not yet agreed to finance anything in the nature of a full space programme, particularly as regards sending a man into orbital flight, it is interesting to note that the potential for doing this is already to some extent in process of development for the military programme. It has been stated[9] that the Blue Streak ballistic missile has the ultimate capability, coupled with an optimum second stage, to lift a load of about 2,000 lb. into a 300 mile orbit; this seems to be about the minimum weight for a manned ballistic re-entry vehicle.

There are several different plans for using Blue Streak with a second stage on top. Using the standard Black Knight research rocket, it is probable that 1,000 lb. could be placed in a 300 mile orbit; but by using the Black Knight power-plant, guidance and control system, and devising a completely different and larger tank system which takes full advantage of the diameter available at the top of the Blue Streak, and its weight carrying ability, it should be possible to put double this weight into the same orbit. See Fig. 6.

Thus, a modified Blue Streak missile and launching complex, plus the basic components of Black Knight with a different tankage system, could conceivably enable this country to put a man into orbit in a time which would not be unrealistic.

Dyna-Soar

This represents the first attempt to put a lifting vehicle (as opposed to a ballistic vehicle) into orbit. It is purely a military project.

The vehicle consists of a glider section, to be developed by Boeing Airplane Co. and to be air-dropped initially from a B-52 aircraft, and a booster section to be developed by the Martin Co. To begin with, a Martin Titan will launch unmanned gliders, and later a larger booster, either Centaur or the 1·5 million lb. thrust Saturn, might be used for the man-carrying version.[10]

It is reported that the military requirement is for a glider to fly at a height of less than 50 miles whilst over its target, which would mean that the structure would be exposed to maximum kinetic heating for an hour or more, as opposed to less than 20 minutes for re-entry from orbit. The design problems are therefore formidable, particularly as regards environmental protection for the crew. Nothing is known of the possible approach to be adopted here however.

N.A.S.A. Nova

This concept is the most ambitious of the National Aeronautics and Space Administration's projects announced so far. See Fig. 7. It envisages a 5-stage rocket being used to take two or three men to the Moon and to return them to Earth in an 8,000 lb. capsule, the gross weight of the fifth stage at take-off from the Moon being 36,000 lb.[11]

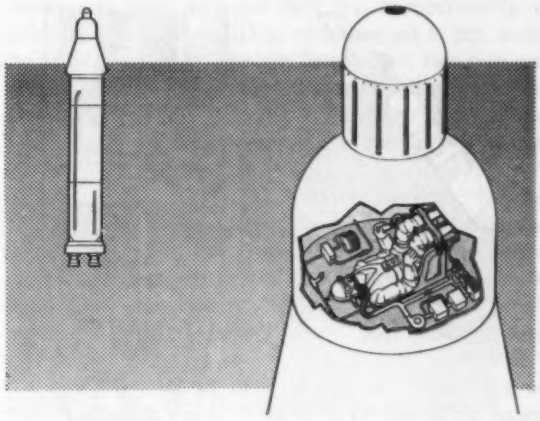


Fig. 6. Possible capsule for Blue Streak/Black Knight.

The total weight of this vehicle would be more than 4,000,000 lb., the exact figure depending on the fuels for the different stages. The overall height would be 220 ft., and the first three stages would be used to place the rest in an elliptical orbit to the Moon. The fourth and fifth stages are for soft-landing on the Moon and the return to Earth. Naturally the re-entry problem here is greater than for an Earth-orbiting vehicle such as Mercury, since the returning capsule will have at least twice the kinetic energy for every pound weight that

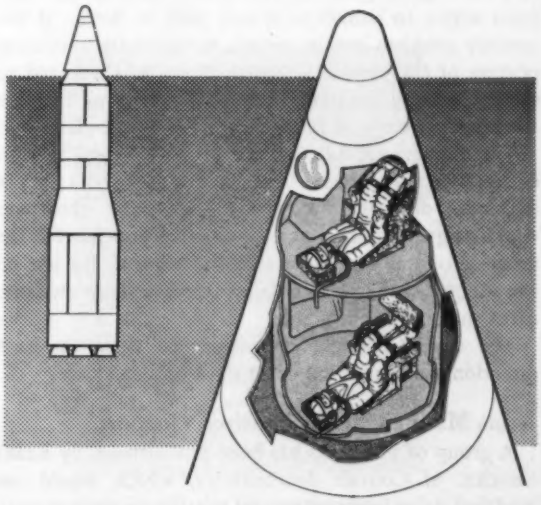


Fig. 7. Possible capsule for N.A.S.A. Nova.

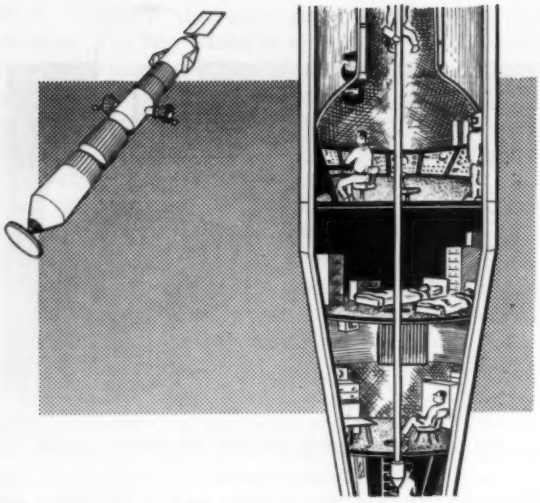


Fig. 8. Convair 'Outpost'.
(By courtesy of British Interplanetary Society)

the Mercury capsule has. Again an ablative surface is envisaged, with a large parachute to bring the vehicle down to sea-level from 30,000 ft. Re-entry from hyperbolic speeds (i.e. speeds in excess of the minimum Earth escape velocity) is chosen, in spite of the difficulties of disposing of the enormous quantities of heat that are generated, because the use of retro-rockets to slow the vehicle even to orbital velocity would involve an initial take-off weight of probably 16 to 20 million lb., which is plainly most impracticable. This incidentally high-lights the fact that whilst a satellite station may be a good place to assemble a lunar rocket and from which to launch it, it may well be better, if the re-entry problem can be solved, to allow the returning portion of the vehicle to return direct to Earth and to use the braking property of the atmosphere to dissipate the kinetic energy of re-entry.

The manned capsule is virtually an enlarged version of the Mercury vehicle, being 14 ft. high and 12 ft. in maximum diameter. Two levels are provided, the lower containing the special contoured anti-g couches for the crew of two or three and a folding air-lock for use on the Moon. Again, little detail on precise crew-environment measures is available.

The times of flight are about 60 hours in each direction, with a period of 12 days on the Moon.

Atlas Manned Space Station 'Outpost'

A group of proposals has been put forward by Krafft Ehricke, of Convair Astronautics, which would use modified Atlas intercontinental missiles to place a small manned space station in orbit. Crews of four upwards are supposed, and the simplest project could be a reality in three to five years, according to Ehricke.[12]

The intention of this programme is to supersede Mercury, and its possible two-man successor, by a more permanent station which could be inhabited continually or intermittently, and which would have a small g-force imposed allowing a more normal existence to a crew. It would enable a whole series of space experiments to be carried out, and facilitate the training of crews for more advanced projects.

The simplest proposal is for 'Outpost I'; this is basically the tank section of an Atlas, modified as described below, which can just be sent into a 350 mile orbit by the Atlas rocket itself. See Fig. 8. This tank section is then used as the external support for a rubberised nylon structure brought up by another rocket; the nylon skin is pushed into the nose and forward portion of the tank and inflated. An air-lock is fitted in the bulkhead at the end opposite to the nose, and three floors installed, one above the other, in the habitable length (or 'height') of 32 ft. When the whole rocket tank structure is set rotating about an axis perpendicular to the rocket axis at 3 r.p.m., an artificial g of ·1 to ·16 is set up in the living quarters; the centre of gravity of the whole structure is kept as far as possible (by placing oxygen, food and water stores and a power reactor at the rear), to keep the value of the attendant Coriolis acceleration as low as possible in the crew compartment. The total weight of such a station would be about 15,000 lb., for a crew of four.

'Outpost II' is a more advanced design with the crew quarters, stores region and nuclear power reactor mutually pushed apart by telescopic booms when the vehicle is in orbit, and 'Outpost III' uses four separate living quarters' sections joined end to end, to support a crew of up to 10. The complete assembly is about 210 ft. long, the four separate pressurised compartments providing very good safety protection against the impact of larger meteors.

To return to Earth, crew-members are intended to use small hypersonic gliders, which would presumably be based on principles evaluated in the construction of such projects as Dyna-Soar, mentioned earlier.

The proposal mentions the use of gaseous rather than liquid oxygen storage.[13] The crew, once installed in their station, would live in 'shirt sleeve' conditions, with pressure suits always available in case of emergency. Absorbents are prescribed for removing carbon dioxide, water vapour and odours, though it would be part of the experimental work of the space station to investigate and develop schemes for recycling the carbon dioxide and water vapour so that the unit would be more nearly self-supporting. Of course it would only be in very large space-stations, or in colonies established

on the Moon and other planets, that the weight and complexity of a fully-closed system would be more than balanced by the saving effected in stores, but the evaluation of such systems will be one of the most important responsibilities of early space-stations such as this Convair proposal.

Lockheed Space Station

This is a very interesting project on which a great deal of detail design time has been spent.[14] See Fig. 9.

It has, therefore, been selected, as involving a group of self-consistent and likely environments, as a basis on which to plan the content of the main portion of this paper. More detailed description of the non-environmental aspect of the project is therefore given, to enable a clear picture to be formed of the overall problem and suggested methods of dealing with it.

The primary aim of this project is to set up a self-contained, permanent space-station in a 500-mile circular orbit. To this end, three-stage booster rockets are used to launch a series of components; the first stage of the booster, giving over 1,000,000 lb. thrust, is fitted with fins and jet-engines and is intended to be recoverable. Launch weight would be about 300 tons for a payload of 20,000 lb.

The space-station proper is a wheel composed of 15 identical tubular sections, each 20 ft. long and 10 ft. in diameter. Five smaller diameter spokes join this rim to a hub region. The rim is rotated at an angular velocity sufficient to give 1g to the occupants, whilst part of the hub region remains stationary, facilitating the unloading of supplies and the exchange of crew members, serving as a zero-g laboratory, and providing a steady platform for astronomical observations. On one side of the central hub, and along its axis, is a boom supporting a nuclear power source and its shielding, and on the other side is a ring structure to which extra storage tanks can be attached, and on to which visiting spacecraft may be guided. An atmosphere equivalent to 10,000 ft. altitude is maintained in the station which is designed to support a crew of 10 men for six months. They would comprise perhaps an astronomer, two physicists, a chemist/photographer, a biologist, two physicians, two electronic engineers, and a machinist/metallurgist.

An interesting feature of this project is the adoption of two auxiliary rocket-propelled vehicles, a re-entry vehicle or 'air-taxi' for two-way communication with Earth, and a general-purpose vehicle or 'astrotug' for assembling the space-station. They are both essential to the satisfactory completion and maintenance of the station.

The air-taxi is carried up into orbit on the nose of a booster rocket in six to 10 minutes, carrying a pilot and three passengers, and can then stay independently in orbit for up to a week. The all-up weight is just under 20,000 lb., the empty weight being about two-thirds of this. A summary of some relevant weights is given in Table II. The return flight into the Earth's atmosphere would take two to four hours, and special provision is made to counter re-entry heating. A thick double skin and insulation is used, with covers over the viewing ports used in orbit. These covers are later jettisoned for subsonic flight, which is assisted by a 5,000 lb. thrust turbo-jet engine designed to give the vehicle a 100-mile range. During this time it 'lands' on the back of a parent aircraft at approximately 25,000 ft. and is carried back to Earth.

Cabin conditioning of this type of vehicle is mentioned in greater detail in the main portion of the paper.

The other vehicle, the astrotug, is in some ways even more specialised than the air-taxi. In shape it is like a squat dumb-bell with living accommodation at each end and an air-lock between the two halves. Surrounding the waisted portion is a set of fuel tanks and four small manœuvring rockets. A crew of four is carried. Again, the total weight of this vehicle is about 20,000 lb. enabling it to be lifted bodily into orbit on the nose of the booster rocket.

The function of this vehicle, which contains external handling arms, searchlights, infra-red illuminator, television camera and so on, is to 'round-up' the various space-station sections which will have been placed within a few miles of each other by radio- and radar-control, and to join them together into the final space-station form. The aim is to enable the working crew

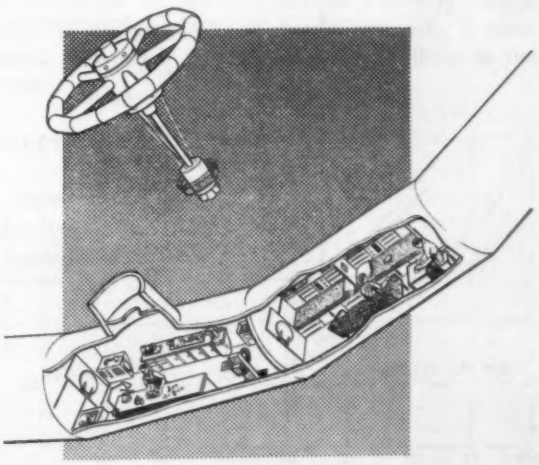


Fig. 9. Proposed Lockheed Space Station.
(By courtesy of Lockheed Aircraft Corporation)

to stay inside their astrotug for the majority of the time, the connecting-up of the sections being achieved by remote control of the external arms.

Again, the environment maintained in this type of vehicle is a subject for more detailed discussion later in the paper.

In neither the astrotug nor the air-taxi is any attempt made to provide simulated-g conditions, as this would be quite impracticable for such small vehicles. Therefore, liquids for consumption have to be supplied in plastic squeeze-bottles. As in all other projects envisaging zero-g conditions for considerable periods of time, only future experience will enable man to decide whether such a course is in fact feasible. Evidence to date seems rather inconclusive, and therefore the results of flights in the X-15 aircraft and Project Mercury capsule are awaited with some eagerness on this score alone.

It may finally be mentioned that the estimated cost of this entire project, involving the construction of launch facilities on a large scale, 10 first-stage and 50 second- and third-stage boosters, 10 air-taxis, 10 astrotugs and the space-station itself, is about £770,000,000; of this about $^{1}/_{7}$ is earmarked for research and development, the remaining £330,000,000 being for actual 'hardware' and facilities. Whilst this is a great amount of money, it may be remembered that the cost of the atom-bomb project up to the dropping of the first two bombs has been quoted as £500,000,000 and several times this figure must have been spent since, in America alone, on nuclear bomb development and production. Thus, the resources for such a project are undoubtedly available should the demand for its realisation mount high enough. Furthermore, this Lockheed proposal has been confined to equipment which could be made without any further 'technological breakthrough' being assumed, merely the normal development to be expected in the time-scale of carrying out the proposal itself.

TABLE II—DETAILS OF LOCKHEED RE-ENTRY VEHICLE AND ASTROTUG

Item	Re-entry Vehicle	Astrotug
VEHICLE WEIGHTS (lb.)		
Total weight	19,600	20,000
Useful load	5,325	7,225
Structure	6,315	3,755
INSTRUMENTATION WEIGHTS (lb.)		
Flight control	1,297	1,315
Communications	740	927
Environmental	117	69
VOLUMES (cu. ft.)		
Cabin	600	760
INSTRUMENTATION POWER LOADS, AVERAGE/PEAK (kw.)		
Flight control	0·835/4·250	0·913/3·210
Communications	0·565/2·625	1·231/3·975
Environmental	0·084/0·824	0·060/0·170

ENVIRONMENTAL REQUIREMENTS AND ASSUMPTIONS

Man in a Sealed Environment

It is obvious that the environmental system requirements must be known before the engineering details can be finalised. The purpose of this section, therefore, is to state the requirements on which the engineering appraisals are based, but as this subject has been dealt with in detail by other authors, it is not intended to justify these assumptions.

The minimum requirements of man are the same irrespective of the nature of his immediate surroundings and these will be stated before dealing with the specific cases which include the re-entry vehicle, the space station, and the lunar suit, in that order. The astrotug and lunar vehicle have been omitted because the re-entry case is the worst as regards environmental engineering and if this can be met, then the others are reasonably straightforward.

THE BASIC NEEDS OF MAN

Food

Man's existence depends on the balance between the intake of fuel and the expenditure of energy, just as in any other machine. The fuel in this case is food, which in one form or another produces energy by oxidation; in addition, by-products and impurities such as carbon dioxide and water vapour are also produced. To facilitate this process an intake of water is also necessary.

The requirements of man under various environmental conditions are shown in Fig. 10, and it will be seen that each day some 2·5 lb. of food, 4·7 lb. of water and 2·88 lb. of oxygen are required at normal temperatures. This total intake will enable him to meet the needs of a normal working day and will result in a nett energy output of 500 B.Th.U's/hr. The intake of food and water is normally a straightforward matter unaffected by environment, although the existence of weightlessness under certain conditions will impose problems to which solutions have already been proposed by other authors.

Oxygen

The intake of oxygen, although largely independent of gravity, is dependent on the partial pressure of the oxygen. For instance, it is impossible to maintain the equivalent of sea level conditions, even in an atmosphere of 100% oxygen, if the partial pressure of oxygen falls below 190 mm. Hg; and without acclimatization, pressures lower than 140 mm. Hg will result in severe hypoxia, leading possibly to collapse. On the other hand, there is an upper limit of partial pressure which is defined by an inflammatory effect on the lungs after a period of time. It is thus possible to produce a band of conditions within which the partial pressure of oxygen must be maintained.

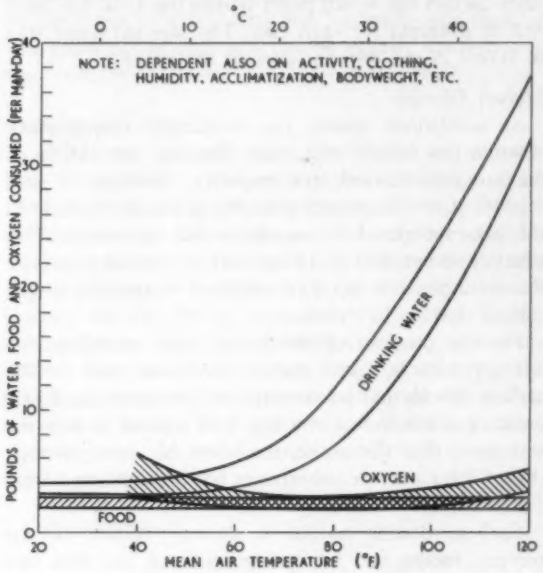


Fig. 10. Intakes of Man.

(By courtesy of the Garrett Corporation of Los Angeles)

Fig. 11 illustrates this band as well as showing the limit of altitude desirable if pre-oxygenation (breathing 100% oxygen) is not possible, and if ascent is rapid. This altitude limit is dependent on the amount of nitrogen dissolved in the blood which is, in turn, dependent on the atmosphere breathed for several hours prior to the decompression. It will be assumed, for the purpose of this paper, that some pre-oxygenation will be practicable for the occupants of a re-entry vehicle and that the possibility of 'bends' occurring is completely obviated in the case of a man walking on the Moon.

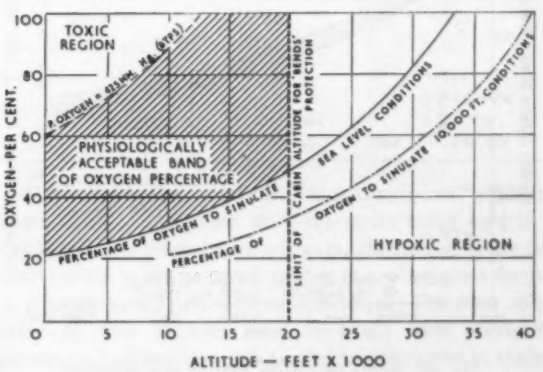


Fig. 11. Range and choice of oxygen percentages.

As the cases being studied are influenced by various other factors the actual point within the available band will be different for each case. The selected point will be stated in the relevant part of the paper.

Carbon Dioxide

As mentioned above, the exchanges taking place result in an output of carbon dioxide. The ability of the lungs to discard this impurity, however, is also dependent on the partial pressure of carbon dioxide in the atmosphere of the environment concerned. This effect is shown in Fig. 12 for various partial pressures, the atmosphere at sea level on Earth containing 0·03% carbon dioxide by volume.

For the purpose of the three cases considered — re-entry vehicle, space station, and lunar suit — the carbon dioxide partial pressure will be maintained at a pressure of less than 4 mm. Hg. This is based on a recent statement that the maximum allowable concentration (M.A.C.) for nuclear submarines has been reduced from 1·0 to 0·5%.[15]

Carbon dioxide output is directly related to the oxygen intake and for the purpose of the first two cases the output will be assumed to be 0·14 lb./hr.; and in the case of the lunar suit where work-rates are higher the oxygen intake will be taken as being 0·3 lb./hr., with a carbon dioxide output of 0·375 lb./hr., for the whole of the period of six hours operation.

Water

The effect of the environment on the output of water from the lungs and the skin, but excluding urine, is shown in Fig. 13. Under all conditions there is a basic

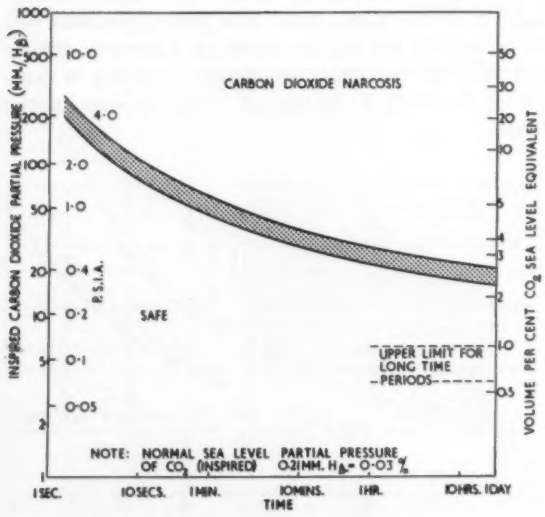


Fig. 12. Effect of carbon dioxide concentration.
(By courtesy of the Garrett Corporation of Los Angeles)

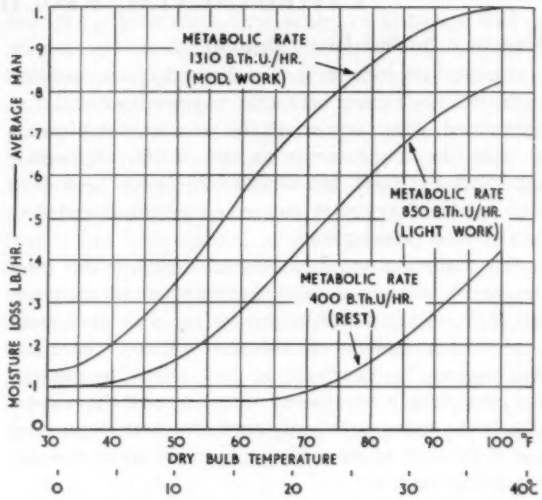


Fig. 13. Water vapour loss from Man.

output of water vapour from the lungs to which must be added the water evaporated from the skin. This latter process is brought into play when the body is having difficulty in rejecting heat due to high levels of activity or if subjected to unfavourable environments. Skin perspiration amounts to approximately 99% water but also includes sodium chloride, various sulphates, glucose, lactic acid, uric acid, carbon dioxide and ammonia. From the system engineering point of view, some 0·25 lb./hr. for each crew member has to be removed.

Temperature

To cover all levels of activity, it is desirable to maintain the compartment temperature at about 68°F. This applies to the temperature of the air and the compartment walls, and an increase in the one should result in a decrease of the other. The space station may best be catered for if the temperatures of certain compartments are maintained at levels consistent with the work to be undertaken in these compartments; for example, a higher temperature may be preferred in rest rooms because the heat output from the body is lower.

To allow the body effectively to reject heat, gentle circulation of the compartment air is desirable and the humidity level of the air should be maintained at about 50% to enable the occupants to perspire if necessary. In the case of the re-entry vehicle, direct personal ventilation and cooling may be desirable if difficulty is experienced in maintaining the required low temperature levels within the compartment during the re-entry phase; otherwise the general figures quoted above apply.

The curves on Fig. 14 indicate the limits that can be set for the most adverse conditions in terms of time for which various temperatures can be tolerated.

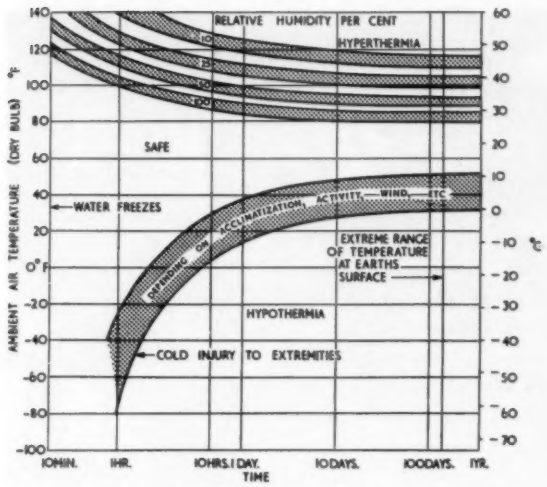


Fig. 14. Temperature tolerances for Man.
(*By courtesy of the Garrett Corporation of Los Angeles*)

TOXIC SUBSTANCES

Odours

These are mainly due to fatty acids, but hydrogen sulphide is present in bowel gases. A toxic level is reached only after a prolonged period of time and removal of the odours will be considered purely from the point of view of comfort.

Carbon Monoxide

This gas is formed by decomposition of compounds containing carbon, and is toxic since it combines with the red blood pigment, haemoglobin. Normally, the lungs give off 10 c.c.'s/day, although this figure is reduced at high oxygen breathing pressures and the gas is also likely to be created from other sources.[15]

Ammonia

This must be considered as it is also given off in urine. Although the M.A.C. value is stated as 0·01% it has the advantage of being sensed at 0·005%. On the other hand it would be dangerous if used as a refrigerant since at 0·04% it becomes a serious irritant to the mucous membrane.[15]

Other Substances

Of the refrigerant gases, Freon 12 and Freon 114 are considered the most suitable, being the least toxic; methyl chloride should be avoided owing to the danger of intoxication.

The results of fire must be considered and only materials that will not cause respiratory hazards must be used in construction of the cabin and its associated equipment. It must be possible to extinguish burning paints, varnishes, and furnishings, without the formation of dangerous fluorinated hydrocarbons which for example can be released by Fluon if heated above approximately 400°F, and attention must also be paid to the types of lubricating and hydraulic oils used, as the 'cracking' of such oils can be equally dangerous in the formation of esters and formaldehydes.[15]

Re-entry Vehicle

It has been assumed that this vehicle will transfer men from Earth to the space station and also return them to Earth. Although the lunar vehicle may be of a different design the environmental requirements for landing the crew on the Moon are assumed to be very similar. In fact, it is easier to cover the conditions of landing on the Moon than re-entry to the Earth's atmosphere as there is no heating condition to be considered. The fundamental considerations affecting the design of the atmospheric conditions inside the vehicle are stated below. This information has been taken directly from the Lockheed proposal[14]:—

Size of Vehicle	8 ft. diameter, 18 ft. long
Cabin Volume	600 cu. ft. approx.
Number of Crew	4
Duration	7 days
Cabin Pressure	413 mm. Hg (16,000 ft. equivalent)
Partial Pressure of Oxygen ...	400 mm. Hg
Partial Pressure of Carbon Dioxide	4 mm. Hg
Partial Pressure of Water Vapour	9 mm. Hg

In addition, heat loads of the electrical instrumentation system, given in the following table, must be taken into account.

TABLE III
ELECTRICAL HEAT LOADS — RE-ENTRY VEHICLE

Instrumentation System	Heat Load	
	Average (kw.)	Maximum (kw.)
Flight Control	0·835	4·250
Communications	0·565	2·625
Environmental	0·084	0·824
Totals	1·484 kw.	7·699 kw.

The Lockheed proposal states that the re-entry vehicle has a double aluminium skin, the outer being 0·05 in. thick and the inner being 0·075 in. thick; the latter is sealed with ⅛ in. gummed rubber in a plasticised form to provide sound and thermal insulation. The pilot and crew of such vehicles must be fitted with pressure garments, helmets, and g-suits, and be restrained in their seats by means of body, head, and arm supports during

the take-off phase. Once in space, it would be possible for them to remove these garments as prolonged use of them will be fatiguing.

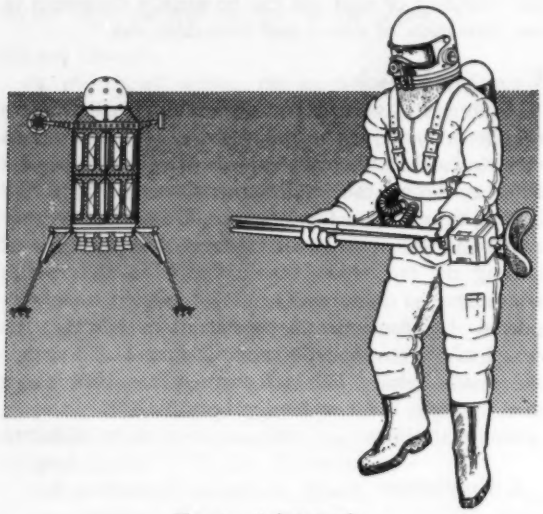


Fig. 15. A lunar suit.

Space Station

The Lockheed proposal[14] assumes that the station comprises a large number of peripheral sections 20 ft. long and 10 ft. in diameter, five smaller radial sections, and a centre hub region with one rotating part and two stationary parts. See Figs. 9 and 30. Since this unit must be capable of orbiting the Earth for many months it is necessary to consider a more economical re-circulation system than that proposed for the re-entry vehicle.

It is considered that the crew should wear normal clothes, and that environmental conditions should conform as close as possible to those on the Earth's surface. The requirements and assumptions for the space station are as follows:—

Number of Peripheral Sections ...	15
Volume per Section	1,560 cu. ft.
Total Volume of Station	50,000 cu. ft. approx.
Cabin Pressure	523 mm. Hg (10,000 ft. equivalent)
Partial Pressure of Nitrogen ...	110 mm. Hg
Partial Pressure of Oxygen ...	400 mm. Hg
Partial Pressure of Carbon Dioxide	4 mm. Hg
Partial Pressure of Water Vapour	9 mm. Hg
Duration of Manned Flight ...	6 months
Number of Crew	10
Orbit Radius	500 miles

In addition, the electrical heat loads given in the following table must be taken into account.

TABLE IV—ELECTRICAL LOADS—SPACE STATION

Item	Heat Load	
	Average (kw.)	Maximum (kw.)
Living and Recreation Quarters	2·9	7·3
Galley and Store-rooms	5·7	53·2
Environmental Instrumentation, etc.	4·2	8·6
Control Room	8·3	26·7
Space- and Bio-medical Sections	5·1	18·4
Physics and Astronomy Sections	6·4	26·5
Chemical Section and Machine Shop	6·6	26·9
Electronics Section	6·5	26·3
Totals	45·7 kw.	193·9 kw.

Lunar Suit

A full-pressure suit is required after landing on the Moon to enable man to leave his space craft to carry out scientific observations. Such a garment, which is shown in Fig. 15, must provide him with a self-contained environment within the limits specified earlier in this paper and must not restrict his mobility to an extent that would lower his efficiency as a scientific observer.

Although the lunar day is equivalent to 14 earth days, the time spent away from the craft would be dictated by habits developed on Earth. A six hour period could probably be contemplated as the time the man could

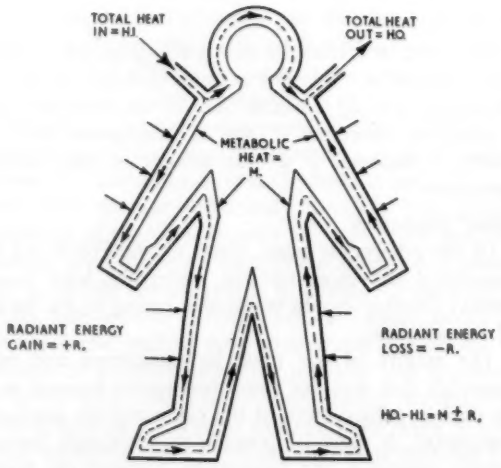


Fig. 16. Heat losses and gains in a pressure suit.

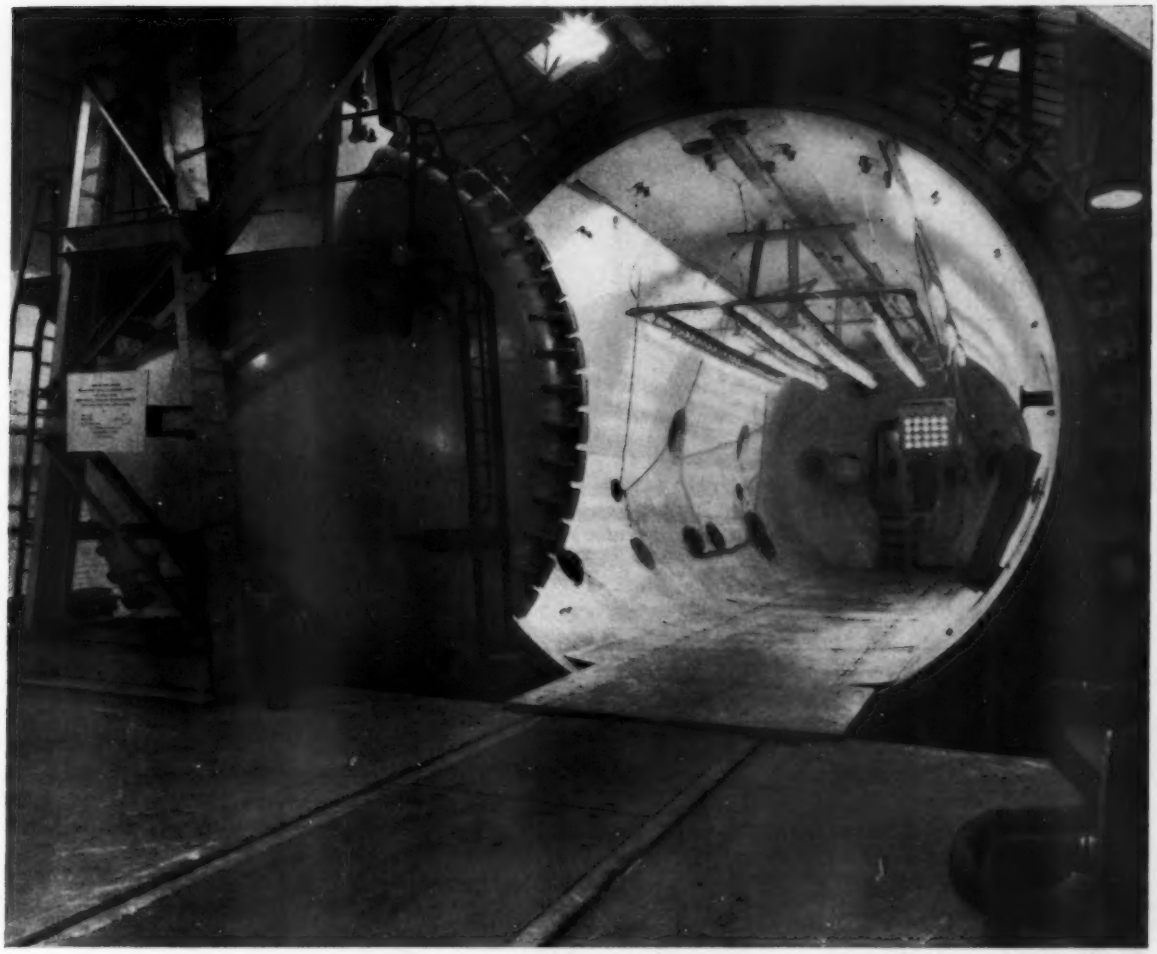


Fig. 17. High altitude chamber showing infra-red heating arrays.

work without a prolonged period of rest or an intake of solid food. This will form the basis of all calculations concerning the lunar suit.

A man walking or working on the surface of the Moon could be expected to consume about 0·3 lb. per hour of oxygen and generate about 1,600 B.Th.U's of energy per hour. In addition he would reject some 0·375 lb. of carbon dioxide per hour and give out about 1 lb. of water.

Although the maximum Moon day temperature would be between 250°F and 300°F, and the maximum night temperature would be about −240°F, the suit must be capable of maintaining the man's skin temperature at approximately 91°F. Normal methods of heat exchange are lost as soon as a man is enclosed in such a garment and Fig. 16 illustrates the way heat may be gained or lost in a suit. It shows that, to cater for all conditions, a circulation of gas over the body must be maintained so that all the heat and water vapour given out can be carried away to be rejected elsewhere.

The effective area of an average man is about 19 sq. ft. while that of a suit will be about 32 sq. ft. and of this about 75% must be considered for heat transfer by radiation to and from outside surfaces. Billingham [18] in a recent paper studied this problem based on a solar-radiation factor of 500 B.Th.U's/hr./sq. ft. and a surface reflection from surrounding terrain of about 25%.

It is known that man can withstand very high temperatures for limited periods of time if suitably clad and tests were carried out in this connection in the Normalair High Altitude Chambers some years ago. In these tests, some being carried out in a chamber similar

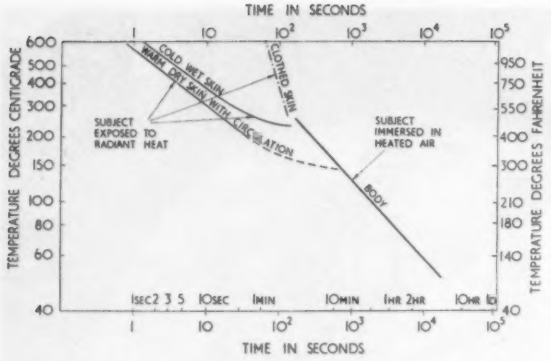

TIME IN SECONDS
TEMPERATURE DEGREES CENTIGRADE
TEMPERATURE DEGREES FAHRENHEIT
COLD WET SKIN
WARM DRY SKIN WITH CIRCULATION
CLOTHED SKIN
SUBJECT EXPOSED TO RADIANT HEAT
SUBJECT IMMERSED IN HEATED AIR
BODY
1SEC 2 3 5 10SEC 1MIN 10MIN 1HR 2HR 10HR

Fig. 18. Short term high-temperature limits for Man.
(From 'Physics and Medicine of the Upper Atmosphere', Chapter XXI, by C. L. Taylor)

to that shown in Fig. 17, a temperature of 212°F was withstood for at least 10 minutes with protective clothing. Fig. 18 indicates the probable periods of endurance for a range of temperatures and this information is likely to be of considerable importance when studying the re-entry problem. Both for re-entry and take-off, a garment of the type contemplated for walking on the Moon could provide emergency protection, the normal supply of ventilating air and oxygen being from the main system of the re-entry vehicle and post-emergency supply being from independent sources.

In the engineering appraisal that follows the method of environmental control assumed will be based on a system utilising rejection of stored water and liquid oxygen. This is possible because the duration of each period of use is short. Water and/or liquid oxygen can provide evaporative cooling and the oxygen can provide, directly, an acceptable breathing atmosphere. Toxic gases such as carbon monoxide will be assumed to build up a concentration so low that they do not create a hazard in the six-hour period and a small rise of carbon dioxide concentration will be accepted for the period under consideration.

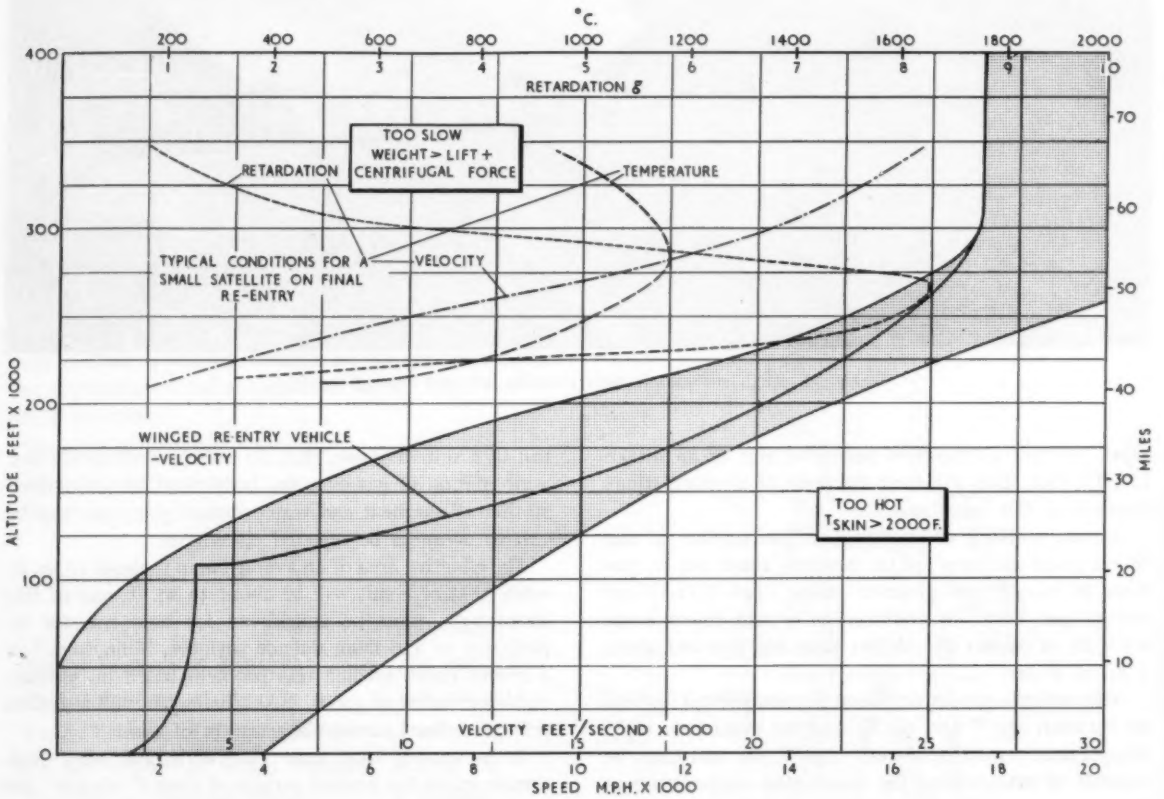


Fig. 19. Flight corridor for re-entry.
(Small satellite data after Nonweiler[17])

ENVIRONMENTAL ENGINEERING APPRAISAL

Re-entry Vehicle

DESIGN CONSIDERATIONS

The environmental conditioning of the re-entry vehicle falls naturally into two parts, the provision of a suitable atmosphere and the cooling of the cabin.

Since the trip is of relatively short duration it has been decided to use liquid oxygen in a converter system and to remove carbon dioxide by absorption with lithium hydroxide. This is mentioned in greater detail when discussing the separate components.

There are several facets to the cooling problem: the metabolic heat load of the crew, the load developed by the electrical and electronic equipment, and the re-entry case which also demands special attention.

Since the re-entry vehicle has to endure very severe kinetic heating during the re-entry phase, effective insulation is provided all over the cabin surface and it is estimated that by using modern super-insulants, such as those manufactured by the Johns-Manville Fiber Glass Division, of the United States, the heat flux into the cabin during re-entry can be kept to a figure comparable with the internal loads. On the other hand, it is not possible during re-entry itself to dissipate an internal heat load by radiation since the skin temperature is far too high. Fig 19 shows a graph of altitude against speed, depicting the 'flight corridor' along which a winged re-entry vehicle would probably return to Earth. Also shown are some lines indicating the temperatures and decelerations experienced by a small ballistic vehicle during re-entry.[17] Whilst a winged re-entry vehicle may be expected to experience a smaller maximum deceleration and peak temperature, it will spend a longer time at comparatively high temperatures. Consequently, almost perfect insulation seems to offer the best approach to the problem, coupled with one of two possibilities; the first is to pre-cool the interior of the vehicle to a suitable level before re-entry so that the ensuing temperature rise is not unbearable to the crew, and the second is to use a liquid such as water, the boiling of which at reduced pressure would absorb the internal heat load during re-entry.

This latter idea is attractive and it has been calculated that the evaporation of 30 to 50 lb. of water, at a temperature compatible with the crew's comfort, would be sufficient to dissipate the internal load during re-entry. However, since the water is rejected overboard in the process, it can be used only once.

Similarly, it is possible to dissipate the internal load during orbiting conditions by simple radiation from the skin of the vehicle, without first raising the temperature level at which the heat is rejected.

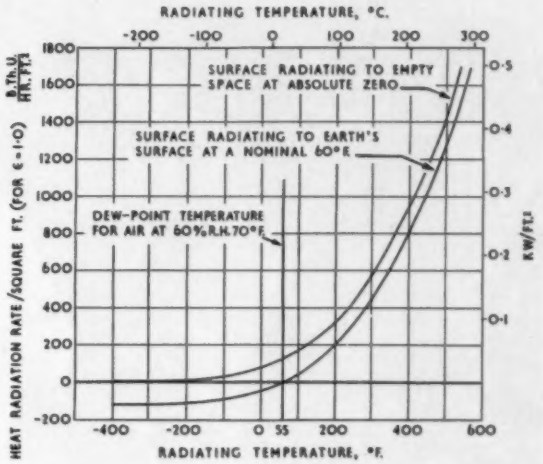


Fig. 20. Heat dissipation from a radiating surface.

GENERAL DESIGN

However, for this particular vehicle it has been thought useful to include a light Freon cooling system which has various advantages for the different flight phases. Firstly, it can be used to condense out exactly the amount of water vapour which is rejected by the crew, at a temperature well above the freezing point of water. This ensures that no icing-up occurs in the water condenser which might otherwise be the case if direct cooling of the cabin air were used.

Secondly, the total radiating area necessary in normal flight conditions can be reduced a little by rejecting the cabin heat at a higher temperature, though this saving is not large. Fig. 20 shows a graph of rate of heat dissipation from a radiating surface to two different environments plotted against radiating temperature.

Thirdly, by running the Freon system at a higher power rating for short periods either normal cooling can be achieved when the condenser area is effectively reduced (e.g. by solar radiation due to incorrect orientation) or the cabin temperature can be reduced prior to re-entry. A drop of approximately 25°F before re-entry is sufficient to keep the final temperature after re-entry to about 95°F.

Fourthly, fine control of cabin temperature is possible by varying the power supplied to the Freon compressor. Some of these points are mentioned in more detail later.

It is true that the electrical and electronic equipment can be cooled separately at a much higher evaporator temperature than can the crew, but it is probably not worth the added complication of two separate systems.

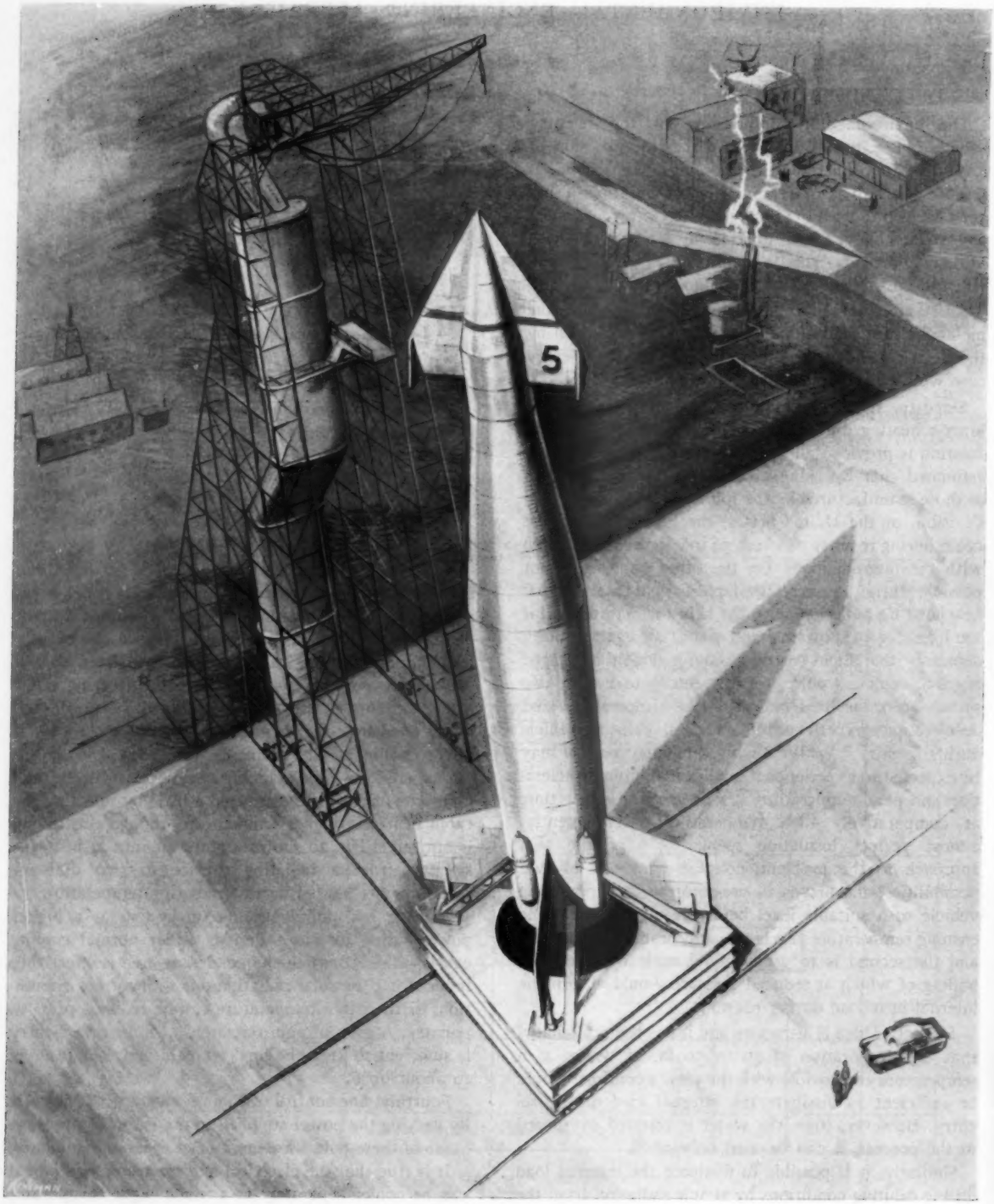


Fig. 21. Booster rocket with re-entry vehicle attached.
(Based on the Lockheed Aircraft Corporation proposal)

For the purpose of weight assessment it is perhaps sufficient to say that in order to dissipate 7 kw. of heat the Freon compressor driven by an electric motor would weigh only approximately 6 lb. and the total Freon cooling system would be less than 40 lb. Fig. 22 shows a typical electrically-driven Freon compressor already in use for aircraft purposes giving a cooling capacity of 120,000 B.Th.U's/hr. The electric motor takes 25 h.p., is Freon cooled, and runs at 24,000 r.p.m. on a 400 cycle A.C. current supply. The total estimated weight of the system is less than 200 lb., including some items which would not be necessary if the heat load were to be rejected solely by radiation. From an engineering standpoint, it will thus be appreciated that the figures quoted for the re-entry vehicle Freon system should be capable of being met.

To return to the actual conditioning of the cabin environment, it may be worth mentioning at this stage that problems posed in such conditioning are not greatly different from those faced in a project on which Normalair Ltd. is already working.

Fig. 23. Simulated high-altitude closed environment test.

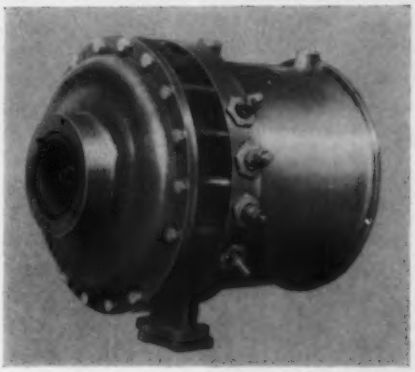


Fig. 22. Electrically-driven centrifugal Freon compressor. (*By courtesy of the Garrett Corporation of Los Angeles*)

In this particular case, the requirement is to condition the cabin of a powered glider which can soar for prolonged periods with engine power off. The only solution appears to be the re-circulation of the compartment air, with any leakage being made up from an oxygen supply, whilst carbon dioxide and water vapour are removed by chemical methods. Fig. 23 shows one of our earlier tests about to commence, and Fig. 25 depicts the type of circuit used. The particular test shown ran successfully for a period of five hours from the time of closing the chamber door.

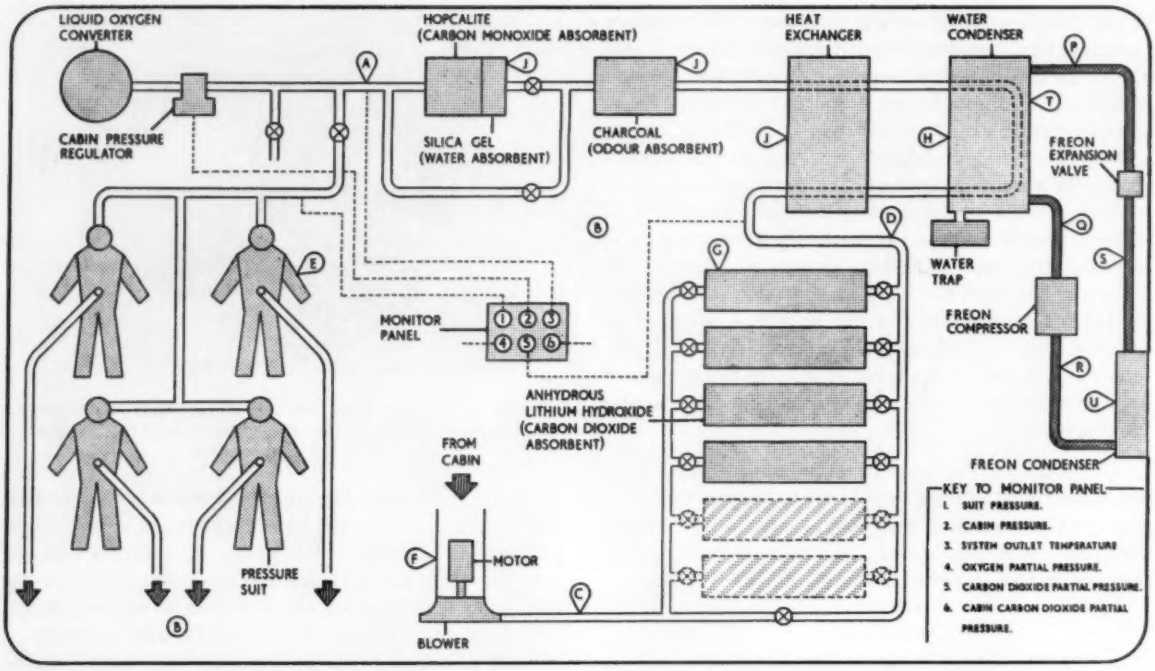
It has been assumed that the closed-circuit oxygen system required for four men for an endurance of seven days is provided by liquid oxygen with carbon dioxide absorption by lithium hydroxide. The general circuit diagram for the system is indicated in Fig. 24. The main components comprising this system are as follows:—

Liquid Oxygen Converters
Pressure Suits
Blower and Electric Motor
Carbon Dioxide Absorption Canisters
Heat Exchanger
Water Condenser (Freon Evaporator)
Freon Condenser
Charcoal Canister
Hopcalite Canister
Cabin Pressure Regulator
Temperature Control System
Freon System Motor and Pump

Some of these components are now discussed in more detail.

Liquid Oxygen Converters

Liquid oxygen has been chosen in preference to high pressure gaseous oxygen as the weight and volume of the equipment is considerably lower than that required for the gaseous system, and it is not considered that the



CONDITIONS IN AIR CIRCUIT

Diagram Reference	Temperature (°F)	Partial pressure (mm. Hg) O_2	CO_2	H_2O	Relative humidity (%)	Flow (lb./hr) O_2	CO_2	H_2O
A. U/Stream of suits	70	410	3·5	9·5	50	272	3·18	3·58
B. In Cabin	79	400	4	12·75	51	272	3·74	4·91
C. D/Stream of blower	110	—	—	—	—	272	2·74	4·91
D. D/Stream of lithium hydroxide canisters	114·5	—	—	—	—	272	3·18	4·91

Component	Pressure Rise (mm. Hg)	Temperature Rise (°F)	Flow Content Rise (lb./hr) O_2	CO_2	H_2O	Enthalpy Rise (B.Th.U's/hr)
E. Suits	−10	9	−·48	0·56	1·33	2,000
F. Blower & Motor	30	31	—	—	—	2,050
G. Carbon dioxide absorbent system	−4	4·5	—	−0·56	—	300
H. Water condenser	−2	− 44·5	—	—	−1·33	−4,350
J. Heat exchanger, etc.	−12	∓ 19·5 for H.E.	—	—	—	0

CONDITIONS IN FREON SYSTEM

Component	Pressure (lb./sq. in Abs.)	Temperature (°F)
P. After expansion valve	15·2	40
Q. After evaporator	15·2	50
R. After compressor	39	101
S. After condenser	39	80
T. Freon evaporator	15·2	40
U. Freon condenser	39	90

Freon flow to absorb 6·2 kw. = 6·6 lb./min.

Coefficient of performance = 7·2

Radiating area (emissivity of 1·0) = 150 sq. ft.

Fig. 24. Environmental conditioning system for the re-entry vehicle.

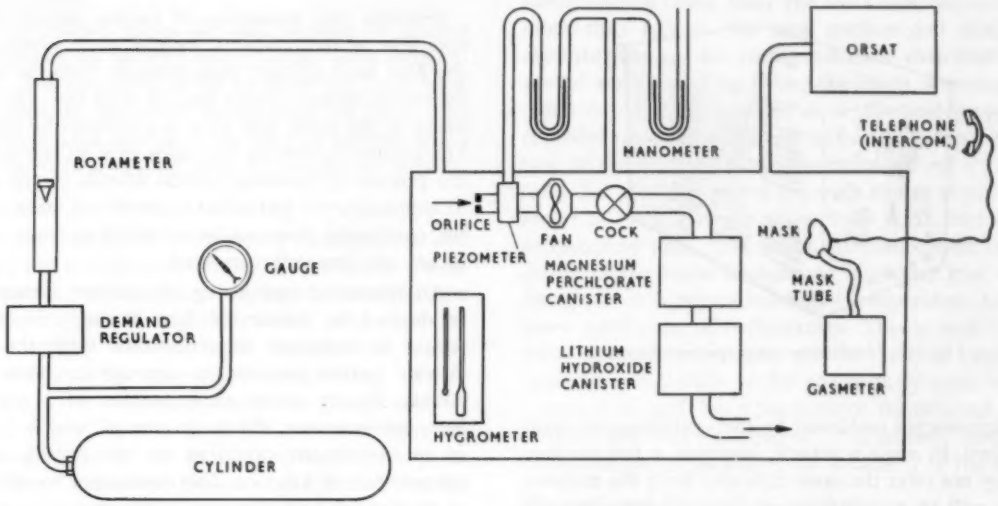


Fig. 25. Schematic diagram of closed environment test.

question of weightlessness need prevent the liquid oxygen converter from operating. Fig. 26 shows a typical liquid oxygen 20-litre converter, of which many are already in existence and in constant use. There should, hence, be no doubt as to the engineering involved in this component. The weight of 89 lb. of oxygen covers the minimum crew requirements for such a journey, plus a leakage factor from the cabin of 0·05 lb./hr.

The weight of such a converter full of oxygen will be approximately 150 lb. complete with evaporator coil and oxygen control valves and the unit will fit into a 20 in. cube. In view of the hazards that might be met in flight it is thought wise to duplicate the system so that the total weight of the liquid oxygen system would amount to approximately 300 lb.

It has already been stated that it is proposed to hold the cabin atmosphere at an overall pressure equivalent to an altitude of about 16,000 ft. and the oxygen regulator shown in Fig. 29 controls the supply of oxygen from the converter to maintain this altitude.

It should be noted that the actual supply of oxygen from the converter is of the order of only 0·53 lb./hr, made up of 0·48 lb./hr for the crew and 0·05 lb./hr assumed leakage rate. As indicated in the section covering the requirements of a pressure suit, this flow is wholly inadequate for the proper ventilation of the crew members in their suits, so that an electrically-driven blower is provided.

Pressure Suits

The fundamental requirements for a lunar garment have already been outlined and the form such a suit will take is described under the appropriate heading later in the paper. Again, as mentioned previously, it is envisaged that the crew would wear the basic portion of the lunar suit, less its cooling system, supply pack and insulating cover, during take-off and re-entry; the cooling and breathing supply in the re-entry vehicle would be obtained from the cabin environmental system as shown in Fig. 24.

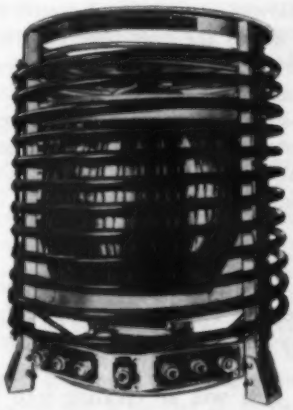


Fig. 26. 20-litre lightweight liquid oxygen converter.

One of the important requirements in the case of a garment to be worn in a confined space is the need to avoid its interference with normal activities.

In the case of full pressure suits designed for use in aircraft, one of the main problems is associated with the headpiece where a reliable means of providing

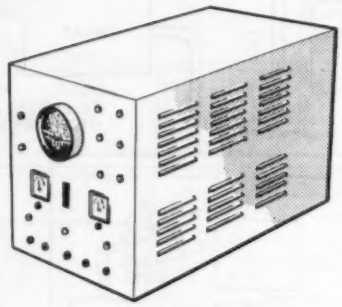


Fig. 27. Monitoring mass spectrometer.

breathing oxygen undiluted by the ventilating air must be devised. In a space vehicle, however, a full pressure suit may not offer the same difficulty since the circulating gas will be enriched oxygen, but if carbon dioxide removal is not catered for a similar situation will arise.

Early pressure suits were constructed from heavy materials and were uncomfortable to wear, but the most recent work indicates that a suit weighing less than 15 lb., including the headpiece, should be available for the proposed application.

Blower and Electric Motor

This blower must be able to circulate about 276 lb. of gas per hour, and in view of the assumed pressure drops and an overall efficiency of about 50% for the motor and blower, a 31°F rise of temperature occurs in the airflow across the unit. The electric motor itself requires 600 watts for operation, and is cooled by the circulating airflow.

If a high-speed motor were used there is no reason why the motor and fan should weigh more than 2 lb., and it is quite easy to design such a motor to run at 24,000 r.p.m. on 3 phase, 400 cycle, A.C. current.

Carbon Dioxide Absorption Canisters

In view of the relatively short duration of flight it has been decided to adopt a simple non-regenerative absorption system for the re-entry vehicle, using lithium hydroxide.

The four men will be creating 0·56 lb. of carbon dioxide per hour, and therefore approximately 95 lb. for the entire duration of the flight. Such a quantity, requiring 1·35 times that weight of lithium hydroxide to absorb the carbon dioxide, necessitates a total absorption weight of 128 lb., and to this must be added approximately 30 lb. for the containers themselves. They would be 12 in. in diameter and 24 in. long, 10 such units being arranged in parallel with a by-pass circuit. See Fig. 24.

Provided that absorption of carbon dioxide is fairly complete in the canisters, only a small proportion of the flow need actually pass through them, as we wish merely to remove carbon dioxide from the cabin atmosphere at the same rate as it is generated by the crew. The lithium hydroxide also adds heat to the system in the process of removing carbon dioxide to the amount of approximately 300 B.Th.U's/hr. By a system of valves the circulating flow can be switched to fresh canisters as any one becomes saturated.

An automatic monitoring and control system would be devised by which the flow through the canisters would be regulated in accordance with the carbon dioxide partial pressure in appropriate parts of the circuit. Fig. 27 shows an impression of a monitoring mass spectrometer, the basic part of which is similar to an instrument produced by the Bendix Aviation Corporation of America. This instrument would be used to monitor the oxygen and water vapour partial pressures in the cabin, as well as the carbon dioxide, and could also detect in extremely low concentrations any toxic gases produced by the crew or equipment. It is worth noting that this instrument requires a high vacuum to be maintained continually, and this is very easy to arrange in the normal environment of a space vehicle. Fig 28 shows another very small and convenient instrument for registering the partial pressure of oxygen, the J.R. Neville partial pressure transducer, the current from which is proportional to the oxygen partial pressure in the gas circulating around it.

It is not easy to regenerate the used lithium hydroxide, and the canisters would either be sealed and stored after use, or jettisoned.

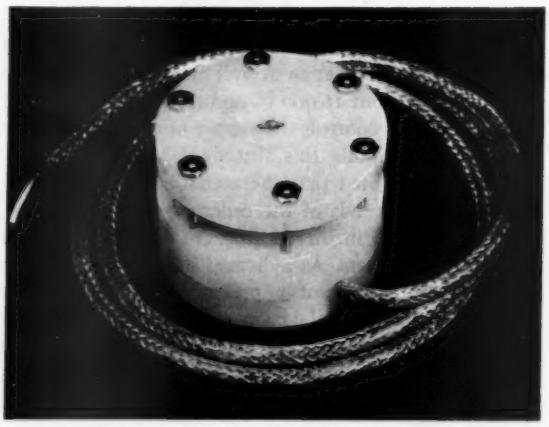


Fig. 28. J. R. Neville oxygen partial pressure transducer. *(Shown actual size)*

Heat Exchanger

This component serves the dual purpose of cooling the circulating air prior to entry to the Freon evaporator, and of warming the dried air from the latter back to the pressure suit inlet temperature of 70°F. The effectiveness need only be 0·305 for this purpose and a simple contra-flow aircraft type unit would be suitable.

Water Condenser (Freon Evaporator)

As already mentioned in discussing the operation and design of the overall environmental system, the Freon evaporator is envisaged as serving for cooling the circulating air, condensing out surplus water, and for cooling electrical and electronic equipment. At the chosen altitude, the dew-point temperature of air containing water vapour sufficient to give a relative humidity of 50% at 70°F is 50·5°F and, therefore, the Freon temperature in the evaporator has been kept to 40°F with 10° superheat. Freon-114 is circulated at the rate of 6·5 lb./min. absorbing in normal use a total of just over 6 kw.; of this total, 4 kw. of cooling is available for equipment other than environmental equipment.

As shown earlier in Table III, the average and maximum equipment heat loads for the re-entry vehicle are approximately 1·5 and 7·5 kw., respectively. Thus, if we assume a continuous maximum of about 4 kw., the Freon system in the conditions stated above will just meet such a load.

Freon Condenser

It is calculated that 150 sq. ft. of surface will be required to radiate the above load to free space, this area representing approximately one quarter of the skin surface of the cabin. Since the Sun's rays cannot fall on more than half of the total surface and since it is assumed than on the average no more than half of the shaded surface will be facing the Earth, it is seen that radiation of this heat load is a practical proposition provided some attention can be paid to correct orientation of the vehicle during the major part of its stay in orbit. For the case quoted it is sufficient to condense the Freon at 90°F giving a theoretical coefficient of performance of more than seven. At the expense of more power to the Freon compressor, a greater load can be dissipated at a higher condenser temperature but at a lower coefficient of performance. This is useful either when suitable orientation of the vehicle cannot be achieved continually, or for the re-entry case, when it is desired to pull down the interior temperature of the vehicle. The latter contingency has already been mentioned earlier, in discussing the suitability of the system.

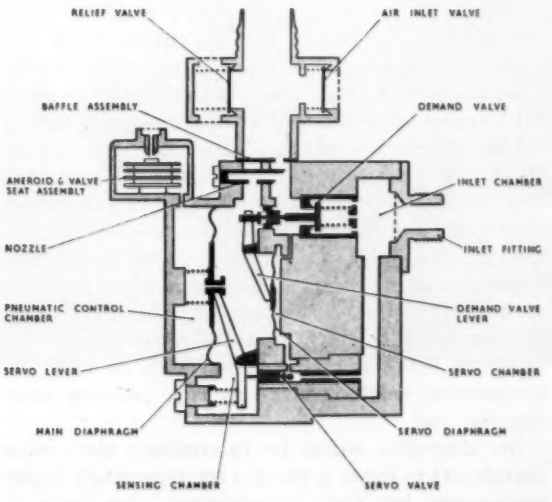


Fig. 29. Schematic arrangement of demand oxygen regulator.

Charcoal and Hopcalite Canisters

The activated charcoal container is for the purpose of removing noxious odours and is not required to be very large for a short trip.

The Hopcalite container must be by-passed so that only a very small proportion of the circulating air actually passes through it, since Hopcalite is rendered ineffective by water vapour and the air from the water condenser is still relatively humid. The air that flows through the Hopcalite, for removal of carbon monoxide, is therefore pre-dried. Again, only a small quantity of Hopcalite is required for a trip of one week's duration.

Hopcalite itself is a mixture, in granular form, of the oxides of copper, manganese, silver, and cobalt, which oxidises the carbon monoxide to the dioxide by catalytic action.

Cabin Pressure Regulator

Where leakage of gas from a sealed compartment in space is catered for by stored oxygen, the form of cabin pressure control is a straightforward matter. The compartment pressure must be maintained at the selected absolute pressure; and a unit is required to sense compartment pressure and, when it drops below an acceptable level, to deliver a flow of oxygen to the compartment. The function of such a unit closely resembles that of a demand regulator commonly used to provide oxygen for breathing in modern military aircraft. Fig. 29 shows a schematic arrangement of a demand emergency oxygen regulator developed by Normalair Ltd. which would provide the basis for a compartment pressure controller of the type required. Operation is dependent on the maintenance of a fixed datum pressure on one side of a sensing diaphragm (main diaphragm) such that a fall of pressure on the other side of the diaphragm results in the opening of a small

servo valve to pass a flow of oxygen. If this servo valve is unable to pass the full flow needed, a second larger valve (demand valve) is opened by the build-up of pressure on a second diaphragm (servo diaphragm) due to the flow of gas through the first valve. In this way, the high flow rates necessary for rapid inflation of current pressure garments are available from the present unit and similar flows could be available to cater for a sudden drop of pressure in a space vehicle, although care must be taken to ensure that this flow can be stopped if the cause of decompression is more than transient in nature.

A photograph of a Normalair regulator of the type which could easily be modified for this purpose is shown in Fig. 41 in the section on Emergencies.

Temperature Control System

As stated earlier, the re-entry vehicle is covered with an effective layer of insulation, for the purpose of maintaining a suitable cabin temperature in spite of excessive kinetic heating during the re-entry phase. Therefore, during orbiting conditions, the internal temperature depends almost wholly on the working and regulation of the environmental cooling system. It is a simple matter to regulate the power supply of the Freon compressor in accordance with the cabin temperature signals, and thus to adjust the internal temperature to the required level.

The weights of the separate components described in this environmental conditioning system are tabulated in Appendix 1 and it will be seen that the total weight is about 600 lb. It must be remembered that double the quantity of liquid oxygen that is strictly required has been allowed, which provides a useful surplus for emergencies. Every part of the system is already a practical proposition and the complete system should require very little further development. It is thus possible to hope that at some time in the future a more sophisticated system, carrying a smaller weight penalty still, could become available even for such a small vehicle.

Space Station

DESIGN CONSIDERATIONS

The analysis of the re-entry vehicle environmental engineering above shows that one of the major problems is the weight that must be carried for the removal of carbon dioxide. With a non-regenerative system this weight is proportional to the endurance, which makes the problem of considerable magnitude in the case of the space station.

For the re-entry vehicle a minimum of 89 lb. of oxygen was required for four men for one week, so that in the space station 10 men will require approximately 6,000 lb. for six months.

Again, the four men for one week exhaled 94 lb. of carbon dioxide requiring 128 lb. weight of lithium hydroxide, so that 10 men for six months would create over 6,100 lb. of carbon dioxide, requiring over 8,300 lb. of absorbent; these again are minimum figures.

These values serve to show the very large weights to be carried if a closed-circuit ecology is not used. By corollary, the successful space station system is the one that approaches nearest to the Earth's own system—because ultimately the interchange of oxygen, carbon dioxide and water vapour in a closed system containing the two types of life, animal and plant, requires a certain amount of energy only, without nett change of weight.

Closed-circuit ecology is discussed in more detail in a later section, and for the moment attention is confined to methods of absorbing carbon dioxide by means which do not necessitate a weight penalty proportional to mission duration. Such methods range from the purely physical to the purely chemical, apart from the biological methods mentioned later.

Amongst the methods available we have:—

Diffusion

According to Graham's Law, the rate of diffusion through a porous body of carbon dioxide is $\sqrt{\frac{29}{44}}$ or ·81 times that of the remaining air; owing to the low initial concentration a fairly complicated cascade system would be required, involving considerable pumping power, and this method does not seem to be the most suitable for a space station.

Freezing Out

The carbon dioxide can, in theory, be removed by condensation in the same manner as water vapour. However, since it is necessary to keep the cabin concentration of the gas below 1%, its partial pressure will be about 0·1 lb./sq. in. abs. and to freeze out completely the gas at this concentration would require a temperature of nearly absolute zero. As an example the freezing temperature of carbon dioxide, which at normal atmospheric pressure is −109°F, has already dropped to −147°F at a pressure of 2·14 lb./sq. in. abs., over 20 times the envisaged partial pressure. Of course, the oxygen and nitrogen would also have liquefied by the time this low concentration of carbon dioxide had solidified, making possible the separation of the gases in the reverse sense, i.e. evaporation of the oxygen and nitrogen before the carbon dioxide re-sublimes; but to bring the entire circulation flow down to such low temperatures would involve very large radiating areas. (See Fig. 20).

An alternative would be to compress the carbon dioxide and to freeze it out at a correspondingly higher temperature but again approximately 100 times its volume of circulating air would also have to be com-

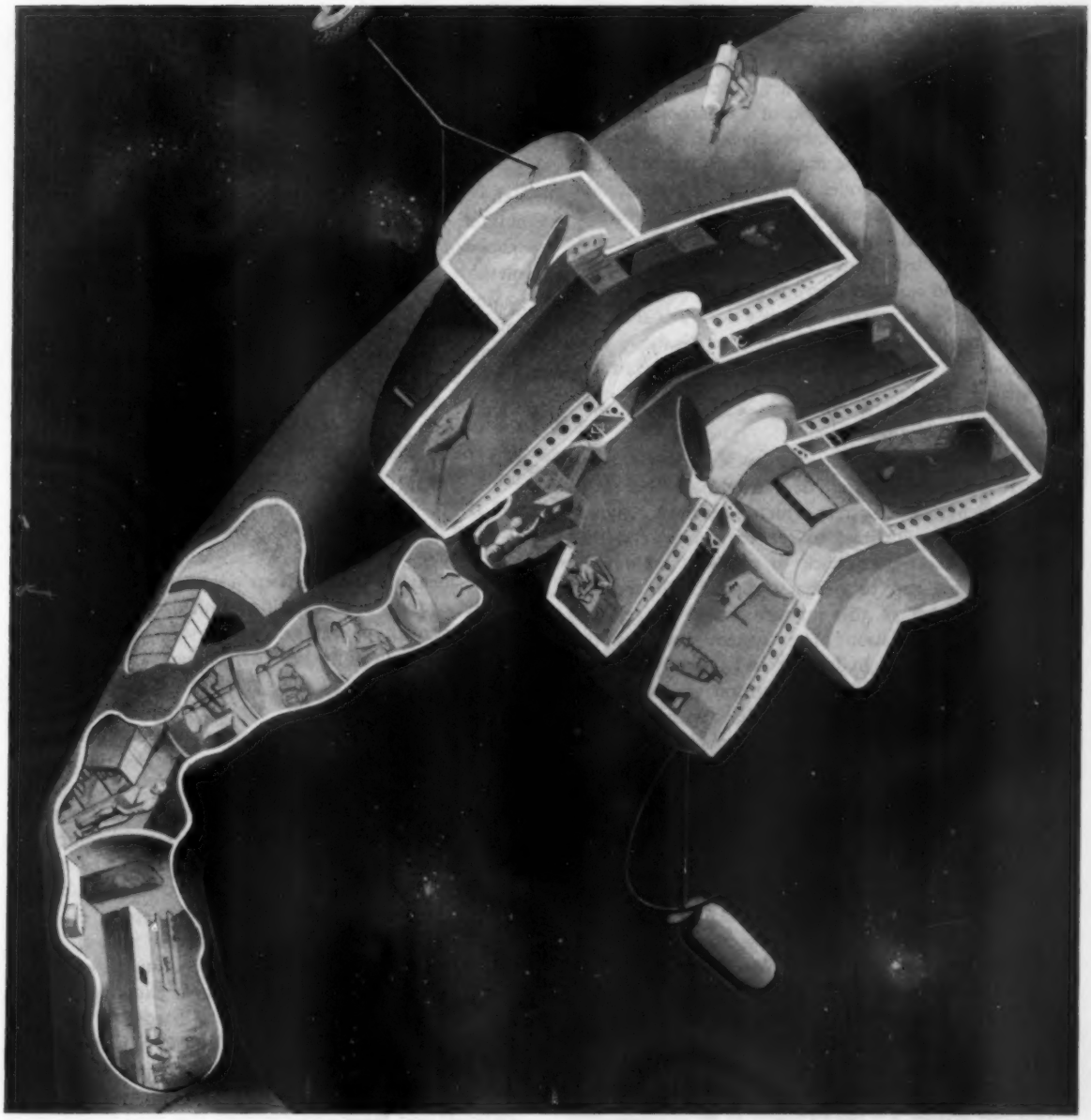


Fig. 30. Sectioned view of space station.
(*Based on the Lockheed Aircraft Corporation proposal*)

pressed, with consequent high power demands and very high pressure ratios.

Dissolving in Solution

A method developed for American nuclear powered submarines involves the absorption of carbon dioxide in mono-ethanol-amine (M.E.A.).[18] Contaminated air is blown down a tower through a mist of cool M.E.A., which absorbs a high proportion of the carbon dioxide. A cyclone separator then removes the M.E.A. mist, and clean air is returned to the main circuit. The M.E.A. is eventually passed to a boiler where the carbon dioxide is drawn off, and the liquid is then cooled and returned for further carbon dioxide absorption. The carbon dioxide is collected from the boiler, compressed to liquid form, and rejected overboard.

Unfortunately no actual figures are available of weights or power requirements, but it seems likely that more power is used than would be considered suitable for a space station.

Chemical Combination

The lithium hydroxide reaction with carbon dioxide is not reversible under practical conditions, but it is possible to envisage a system which in essence converts calcium oxide (quicklime) to the carbonate, and this latter can be converted back to calcium oxide with suitable heating, up to perhaps 1600°F. The carbon dioxide driven off in this manner would be rejected from the space station. The system involves the formation of calcium hydroxide and possibly calcium bicarbonate, with attendant absorption and release of water, but it is quite possible that with sufficient development such a system can be made to operate successfully. This would mean that only relatively small quantities of chemical absorbent would need to be carried, even for journeys of long duration.

Molecular Sieves

These are synthetic zeolites with the property of reversibly absorbing carbon dioxide and other gaseous or liquid substances. This is effected by trapping the molecules in the small pores in the zeolite lattice. Two types are manufactured under the name of Linde Molecular Sieves, which have well defined pore diameters of either four or five Angstrom units. The absorbed gases may easily be driven off by heating, and either purging with air or venting to a vacuum.

This last system has been chosen as an example of a regenerative absorption method for the purpose of this paper, and it is now proposed to detail an environmental engineering system utilizing such absorbents.

GENERAL DESIGN

The total volume of the space station has been taken to be approximately 50,000 cu. ft. The electrical and electronic loads for various sections are shown in Table IV, from which it is seen that a maximum of nearly 200 kw. is to be dissipated. However, it seems reasonable to estimate a normal maximum of approximately 60 kw., and bearing in mind the skin radiating surfaces that are available it is found that the latter load can easily be rejected at a skin temperature leading to acceptable conditions for the crew. It is, therefore, envisaged that temperature control for the space station will be achieved by the suitable circulation of air internally, coupled with the radiation of surplus heat from suitable areas which may be varied mechanically using insulated shutters in accordance with comfort requirements.

Since the space station is going to be inhabited for long periods, damage to individual sections by meteors cannot be discounted although light shielding would prevent any but large particles from breaking through. For this and other reasons it is proposed to split up both the oxygen supply equipment and the carbon dioxide absorption equipment into five self-contained groups of units disposed symmetrically around the periphery of the space station. (See Fig. 31). As in the case of the re-entry vehicle, liquid oxygen has been selected for this system.

The idea has further been adopted of making each section of the station as self-contained as possible. Also, in the event of an emergency, any section could be cut completely out of the environmental conditioning system. Reference to Fig. 31 shows that this system embodies two ring-mains, one for supplying fresh air and the other for extracting and conditioning stale air, and by the use of shut-off valves any section can be cut out of the system at will.

Each of the five sub-systems has been designed to condition the air for four men continually. Since the crew comprises 10 persons, a safety factor of two is thereby achieved. Briefly, oxygen is supplied to the fresh-air main, being made available wherever required, and stale air is drawn by fans into the stale-air main. From there it passes to one of five units, in each case via a three-way valve to a skin heat exchanger where water is frozen out completely. The dried air then passes to a zeolite canister which is shielded from solar radiation by a reversed parabolic mirror. Here the carbon dioxide is extracted and after passing through the usual charcoal and Hopcalite canisters the conditioned air is fed to the fresh-air main.

At the same time, ice in the alternative heat exchanger is melted out by cabin heat, and carbon dioxide is driven off from the zeolite container to space by solar heat focused by means of a parabolic mirror, which is the duplicate of the one mentioned above.

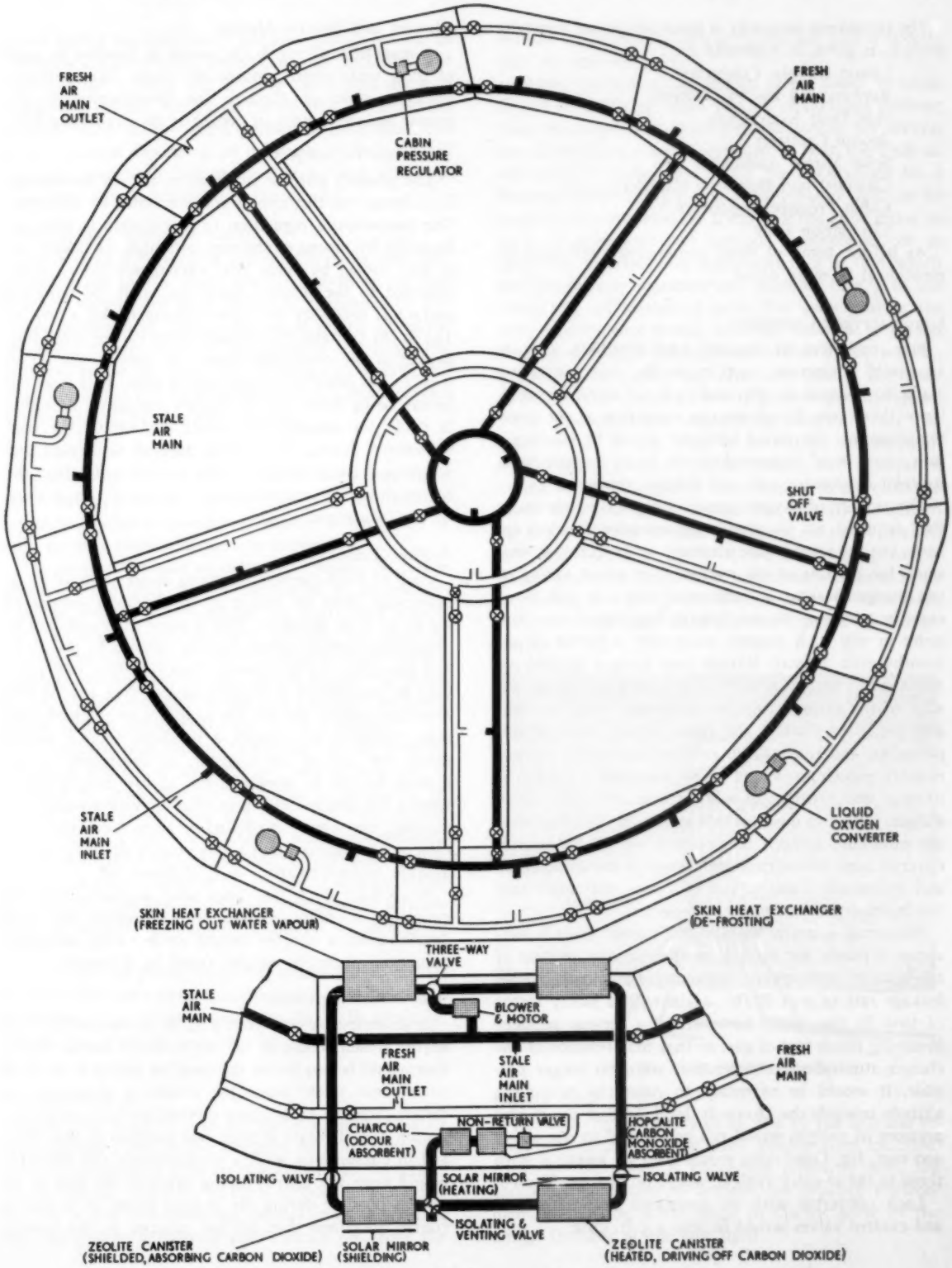


Fig. 31. Environmental conditioning system for the space station.

The equipment necessary is listed below and a weight analysis is given in Appendix 2.

Liquid Oxygen Converters
Blowers and Electric Motors
Skin Heat Exchangers
Zeolite Canisters
Solar Mirror Assemblies
Charcoal and Hopcalite Canisters
Cabin Pressure Regulators
Circulation Fans

As before, some of these components will now be mentioned in more detail.

Liquid Oxygen Converters

Five converters are required, each weighing, with its associated equipment, over 2,700 lb., and containing 2,400 lb. of liquid oxygen and 75 lb. of liquid nitrogen. Since these two liquids do not evaporate at the same temperatures, the liquid nitrogen would be contained in a small vessel immersed in the liquid oxygen, with its own evaporator coil and control valves.

The amount of oxygen quoted is approximately twice that required on an average-consumption-plus-leakage basis, but the leakage rate assumed, 0·172 lb./hr, is very small for the size of the station, even when adding in the nitrogen leakage as mentioned below. It will, however, be necessary to cut leakage losses to a very low order in any such project, since over a period of six months even a small leakage rate gives a prohibitive cumulative weight penalty. For instance, taking the ratio of the surface areas of the re-entry vehicle cabin and the space station, the ratio of their atmospheric pressures, and the leakage rate quoted earlier for the re-entry vehicle, a weight of no less than 8,500 lb. of oxygen and nitrogen would be required in a space station, purely to meet leakage losses. By carrying twice the minimum oxygen requirement we do, of course, cover to some extent the contingency of any unexpected and irreparable leakage, but this does not mean that the leakage problem may be neglected.

The small quantity of nitrogen carried in each converter is purely for making up the nitrogen content of the station atmosphere, assuming the small overall leakage rate of 0·21 lb./hr, again with a safety factor of two. In the event, however, of a serious accident involving much loss of gas, so that maintenance of the chosen atmospheric composition were no longer possible, it would be necessary to *raise* the equivalent altitude towards the 16,000 ft. level, so that the partial pressure of oxygen would not be allowed to rise above 400 mm. Hg. Conditions would then be identical with those in the re-entry vehicle, where no nitrogen is used.

Each converter with its associated evaporator coil and control valves would fit into a 5 ft. cube.

Blowers and Electric Motors

A mass flow of 125 lb./hr would be handled by each of these units which absorbs 280 watts. They serve to circulate stale air through the conditioning system proper and the motors are cooled by the circulating flow.

Skin Heat Exchangers

The primary purpose of these, as already mentioned, is to freeze out the surplus water exhaled by the crew. The temperature regulation of the station is obtained basically by means of shutters, although, of course, air is also cooled by these heat exchangers before being returned to the system. About 60 sq. ft. of radiating surface is necessary for each exchanger, and a flow of 125 lb./hr contains the surplus water vapour from four people in the conditions stated. By cooling the air to −40°F it is dried to a very high degree, as is essential before being passed to the zeolite container. Provision is made for covering the outer surface of the heat exchanger during the second part of the cycle and warming it from inside, in order to melt and collect the frozen out water vapour which can thereby be drained off for future use.

Zeolite Canisters

Each of these canisters contains about 40 lb. of Linde Molecular Sieve 4A pellets in a cylindrical volume of 2·5 ft. by 8 in. diameter. This is more than sufficient to absorb the surplus carbon dioxide exhaled by the crew, and the cabin carbon dioxide concentration will probably be maintained at a figure of less than 1%. Whilst absorbing carbon dioxide, the canisters are shielded from solar radiation by rotating a parabolic section mirror about the axis of the canister, as absorption of the carbon dioxide is more efficient at low temperatures. During the alternative phase, shut-off valves isolate the canister, the mirror is rotated so as to focus the Sun's rays on the canister, and a valve opens allowing carbon dioxide to vent to space as it is driven off.

A six-hour cycle has been used in calculating the quantities of zeolite required but it is probable that with development a shorter period cycle, with attendant reduction of zeolite weight, could be achieved.

Solar Mirror Assemblies

A projected area of about 9 sq. ft. is required for each mirror which would be of thin polished metal. Insulation would be applied to the back, to enable it to act as an efficient shield when the zeolite is absorbing the carbon dioxide. An actuator control led from inside the station would rotate it from one position to the other, and in conjunction with a photo-electric cell assembly would keep the mirror facing towards the Sun as far as was possible during the heating phase. It is not, of course, imagined that all five mirrors in the heating

phase would simultaneously and continually be able to intercept the maximum amount of solar radiation, but the six-hour heating and cooling cycle will allow a reasonable margin. The space station will, of course, be in the Earth's shadow for a portion of each orbit, the actual fraction depending on the angle of the plane of the orbit both with that of the Equator and with that of a plane perpendicular to the Sun's rays.

Charcoal and Hopcalite Canisters

There is no difference in principle between the components used in the space station and those for the re-entry vehicle and they will not, therefore, be discussed further here. Due to the use of zeolite sieves for absorbing carbon dioxide, the charcoal and Hopcalite canisters are in the nature of backing-up components, since the zeolite will itself probably absorb much carbon monoxide and other waste material.

Cabin Pressure Regulators

Each of these regulators consists of two independent units, an oxygen and a nitrogen pressure regulator; a complete regulator assembly is inserted downstream of each liquid oxygen/nitrogen converter.

The oxygen pressure regulator unit would be rather similar to the item already mentioned in connection with the re-entry vehicle system. An instrument, detecting the oxygen partial pressure, provides the signal to actuate the regulator, the object being to ensure that a level of 400 mm. Hg oxygen partial pressure is maintained. Monitoring instrumentation would be generally similar to that proposed for the re-entry vehicle.

A regulator unit similar to the one in the re-entry vehicle is placed in the nitrogen supply line, and is arranged to pass nitrogen sufficient to maintain an overall cabin pressure of 523 mm. Hg. This system automatically caters for the case where unscheduled loss of atmosphere in some sections of the space station has prematurely exhausted the supply of leakage make-up nitrogen and the equivalent atmospheric altitude must be allowed to rise to 16,000 ft., as mentioned earlier.

Due to the adoption of the ring-mains system and its attendant shut-off valves it is anticipated that the supply of oxygen to the space station will always be adequate, even in the event of relatively heavy damage to parts of it.

Circulation Fans

Unlike the re-entry vehicle case, the amount of air circulated for conditioning purposes does not represent sufficient ventilation flow for the crew, and, therefore, simple fans are available in each section. In particular sections where overpowering odours may be created (e.g. the galley) additional fans extract air from the vicinity of equipment such as stoves, and pass it directly into the stale-air main.

Before concluding this section of the paper, mention should be made of some further advantages deriving from the adoption of the ring-mains system. An obvious one is that points can be arranged, in both the fresh-air and stale-air mains, into which the connections for a fire-fighting breathing set or a full pressure suit can be plugged. This would make it easy for the crew either to work in poisonous and noxious atmospheres, or to carry out operations on equipment in a section which was temporarily depressurised, without having to use completely self-contained suits. The suits used in the latter contingency would however have to withstand internally the main cabin pressure of 10 lb./sq. in. abs., unless a pressure-reducing valve were used in the fresh-air line, and the stale air allowed to discharge into space.

The environmental engineering necessary for the space station is thus seen to be within the scope of present-day practice, in similar fashion to that required for the re-entry vehicle or for a vehicle to travel to the Moon. It is interesting to note that a complete system for 10 men for six months, duplicated for safety, weighs only approximately 1½% of the total weight of the space station. Even this small percentage can be reduced by moving to a partly-closed-cycle ecology, some steps in the development of which are detailed in a later section.

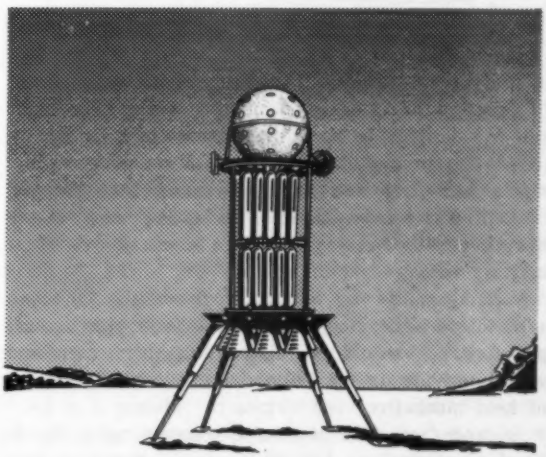


Fig. 32. Moon landing vehicle.

Lunar Suit

The basic requirements to be met by the suit and its associated control system have already been specified. Although the paper is concerned primarily with the equipment necessary to achieve the required environment, it may be worth-while to discuss some of the design features of the suit itself.

DESIGN CONSIDERATIONS

The human body is provided with an extremely high degree of mobility by a combination of hinge and ball joints. Fig. 33 indicates the most important of these joints and clearly shows the problem which a designer of a totally enclosed and pressurised garment has to face. The suit designer has to utilise hinge and rotational joints to cater for all these movements since a tailored garment becomes almost rigid when pressurisation is applied.

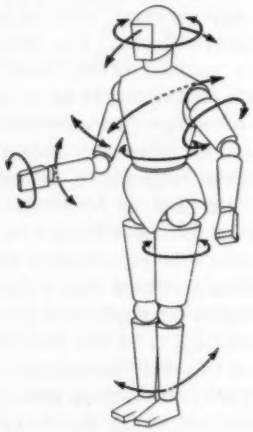


Fig. 33. Diagram of body movements.

Some years ago, Normalair Ltd. were given the task of studying this problem purely from a mechanical point of view and the result is shown in Fig. 34. This particular suit was designed to operate at differential pressures up to 4 lb./sq. in. and although the basic mobility requirements were achieved at this pressure, the original concept was impracticable as it became clear that a man dressed in this way could not be installed in many military cabins.

Such a garment may prove more practicable for Moon exploration since it affords positive protection against punctures; it would be relatively light to wear and would provide an ideal foundation for the provision of heat insulation.

A more recent British suit, manufactured by P. Frankenstein & Sons Ltd., is shown in Fig. 35 and is assumed, in the paper, to be the type used as a means of protection in the re-entry and lunar vehicles. The suit would be of multi-layer construction, and made of fabric throughout.

The basic clothing worn by the astronaut would be a pair of lightweight Terylene trousers, and a string vest similar to the type used by the Kanchenjunga climbers. A ventilation garment comprising a nylon suit to which are stitched ventilation tubes capable of distributing a flow of at least 1 lb. of gas per minute over the body is necessary for the removal of heat and water vapour, which are created by the natural tendency to sweat. This suit would be worn over the basic clothing mentioned above.

On the inner surface of this main garment will be a hydroscopic lining covered by an airtight sheath of fabric backed by foam silicone rubber 1 cm. thick to help distribute the weight of the outer pressure suit. This latter feature has been difficult to cater for in the recent development of pressure suits.

To reduce the effect of the wide range of outside temperatures, a layer of insulating material must be provided over most of the outer surface of the suit. The use of one of the insulants such as Johns-Manville have developed in the United States will reduce the flow of heat entering the suit to about 45 B.Th.U's per hour, or to half of this figure for the heat going out. This insulation is a laminate of thin aluminium foil and silica fibres and is basically similar to that used for missile cones, where a laminate of steel is employed.

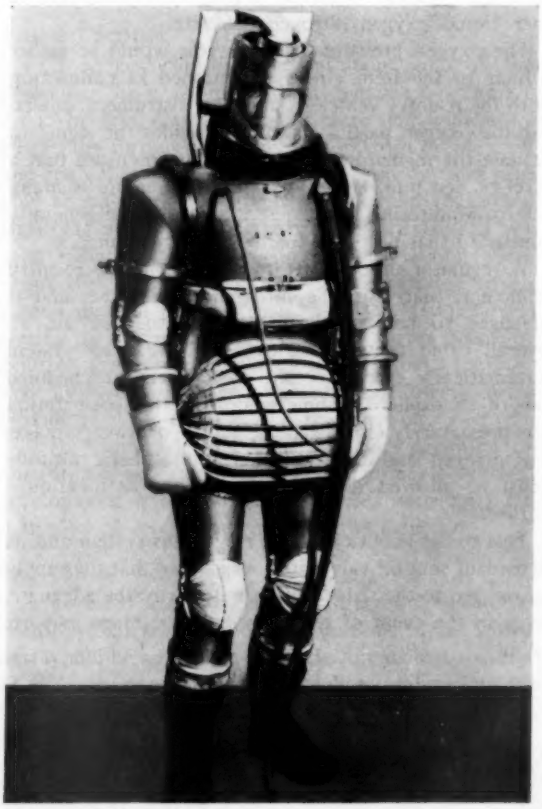


Fig. 34. Normalair early experimental full pressure suit (rigid type).

The soles of the boots could also be constructed of the same material. A thickness of 1 cm. over 1 sq. m. of the suit area, and 0·25 cm. over the remaining 2 sq. m. would be sufficient, and as it would weigh only about 2 lb. on the Earth, the weight penalty on the Moon would be negligible.

GENERAL DESIGN

Having briefly mentioned the general form of the pressure garment necessary to enable a man to walk on the surface of the moon, it is now proposed to discuss in detail the equipment which must be designed to cater for his needs in this suit.

There are two basic problems to be faced; one is the removal of heat from the garment and the other the provision of a breathable atmosphere. It is possible to treat these cases separately, or jointly, and to design the garment accordingly. Irrespective of the equipment used, it will be assumed that the suit will be designed so that the surrounding conditions will not influence the heat to be extracted from the garment.

Fig. 35. Frankenstein full pressure suit.
(By courtesy of P. Frankenstein & Sons Ltd.)

The working pressure selected for the main suit is 3 lb./sq. in. abs. which represents the safe limit of altitude if pre-oxygenation is possible. Assuming the outputs of carbon dioxide and water vapour to be as stated previously, the gas flows required to maintain the impurity level to the figures already defined are shown on Fig. 36, but to cater for the heat output, higher flows are essential if the temperature gradient within the suit is not to be excessive.

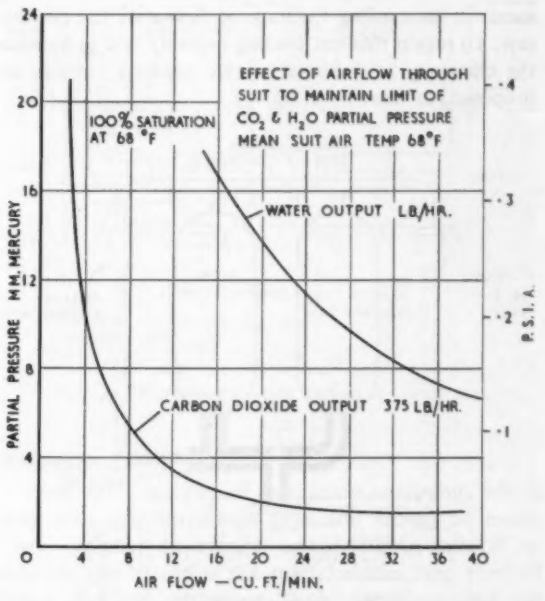


Fig. 36. Ventilation airflows required for a pressure suit.

A supply of 8 cu. ft. of gas per minute free of carbon dioxide, will result in a carbon dioxide level not exceeding 6 mm. Hg finally being reached. Therefore, from the point of view of breathing requirements, a flow of this order could achieve satisfactory conditions. It will be seen, however, that to remove all the water vapour produced at the same time a flow of some 30 cu. ft. per minute of dry gas must be circulated.

As it is possible to supply the environmental conditioning by several different methods, each having its own merits, it has been decided to describe in more detail two of the most attractive systems. The first, called the Liquid Oxygen Evaporation System, depends on liquid oxygen for breathing, cooling, and ventilation. The second system, called the Water Evaporation System, uses liquid oxygen for breathing, the evaporation of water for cooling, and an electrically-driven fan for ventilation. The latter system although more complex is considered superior due to its lighter weight.

Liquid Oxygen Evaporation System

In this system, it is proposed that the oxygen introduced into the system should provide the means of circulation and should also provide the means of drying the circulated gas. This will be achieved by passing the liquid oxygen through vaporisers in the path of the gas flow so that the water vapour would condense on them.

However, in such a system most of the water condensed out would become frozen, tending not only to lower the efficiency of the vaporiser, but also losing some of the cooling capacity of fusion of the condensate. To regain this lost cooling capacity and to increase the efficiency of the system, two separate circuits are proposed, as shown in Fig. 37.

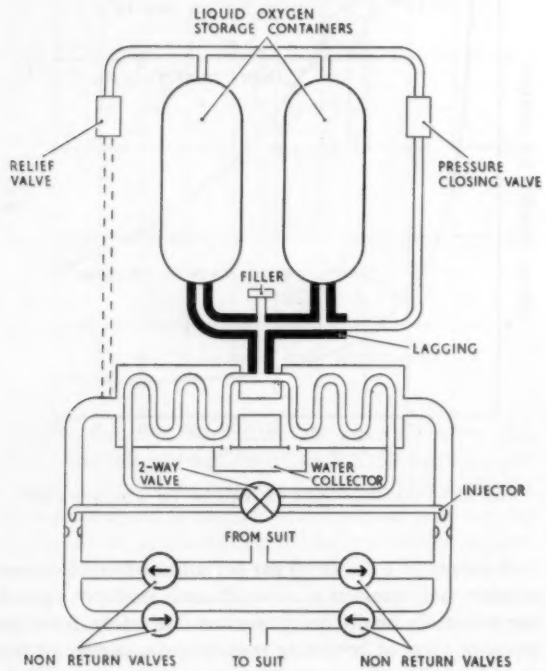


Fig. 37. Liquid oxygen evaporation system for lunar suit.

In this system, oxygen flows for a time through one coil and one ejector, and then reverses so that the ice in the first coil melts so as to pre-cool the gas before it passes through the second coil, on which further ice is formed. Any water created in this process is collected in a drain tank. If the circuit is revised slightly so that the water in the tank is continuously exposed to space, further cooling will be available; by locating the pressure control valve for the suit in the tank, such an outward flow would be possible without endangering the operating pressure control of the system.

An analysis of the weight of a system which would achieve the basic operation described above to control suit pressure to 3 lb./sq. in. for a period of six hours, shows that 43·5 lb. of oxygen will be required. Such a quantity would be stored in two containers for convenience of installation on the crew member's back, at a weight of possibly 10 lb. each. The two heat exchanger circuits would weigh about 6 lb., and the miscellaneous piping and valves might weigh a further 4 lb. Therefore, a total weight of under 75 lb. a set is available to extract 1,600 B.Th.U's per hour for six hours.

The likelihood of a man working at this rate continuously for such a period of time is most unlikely, but even if this were possible the weight of the set would not be prohibitive in terms of the Moon's gravity, since the weight would effectively be only about 13 lb.

Water Evaporation System

It is possible, however, to devise a set appreciably lighter, although more complex in its operation. Such a set would be on the lines of that shown in Fig. 39.

In this arrangement, the cooling is achieved by using water as the medium to be evaporated. Water has a heat extraction potential of 1,030 B.Th.U's/lb., compared with liquid oxygen at only 154 B.Th.U's/lb., if expanded to vacuum conditions. Unfortunately, it is unable directly to provide motive power for circulating the ventilating gas or maintaining the carbon dioxide at a

Fig. 38. Astronaut entering Mercury capsule.
(By courtesy of Shell Aviation News)

low level. It is, therefore, necessary to make a separate provision for the removal of this carbon dioxide.

At the absolute pressure of this garment, the amount of oxygen likely to be inspired directly from an oxygen supply is unlikely to exceed 8½ lb. for the six hours' period even if a high work rate is maintained. This compares with an actual consumption of about 2 lb. of oxygen and an output of some 2·5 lb. of carbon dioxide for this period, the latter requiring 3½ lb. of anhydrous lithium hydroxide to remove it.

Bearing in mind that the presence of a lithium hydroxide absorption bed would increase the power required for circulation and would contribute some heat output because of the chemical reaction, it is felt that any slight advantage in weight achieved by using lithium hydroxide would be negligible.

It is, therefore, possible to choose a system in which oxygen is breathed directly from the storage supply since this is simpler than adopting a re-circulated breathing system. This choice would not necessarily be possible at higher suit pressures since the oxygen consumption would increase noticeably.

In the system proposed, therefore, the cooling would be achieved by controlling the flow of the water from the storage container through a heat exchanger coil to the Moon's atmosphere, which is a near-vacuum. A relief valve would be desirable to prevent the water freezing in the heat exchanger coil as a result of the evaporation, at the expense of its own sensible heat.

Water would be condensed in such a system, and could be used as a source of cooling by being transferred to the storage container. As the container would be pressurised from the ventilating circuit, such a transfer of condensate would be relatively straightforward and automatic with the displacement of the liquid in the container. If used as a subsequent means of cooling, the 0·6 lb. of liquid condensed in the tank would, therefore, require only about 3 lb. of liquid in the first instance. Low work rate levels result in lower water outputs but equally lower heat outputs. The oxygen used for breathing purposes would also provide some supplementary cooling, though it is probably advisable to look upon this as a useful bonus.

Circulation of the ventilating gas will be done by the electrically-driven fan using a battery. A suitable fan and motor would weigh some 4 lb. and would consume 20 watts. The battery for this power would weigh about 4 lb.

Analysing the weight of the system just described, it would appear that the total weight need not be more than 40 lb., and it would be less bulky than the first system described. Of this 40 lb. some 12 lb. would be consumable compared with about 40 lb. for the previous system and this would reflect in initial take-off weight. It therefore appears that a system of the type described using a water evaporator is to be preferred.

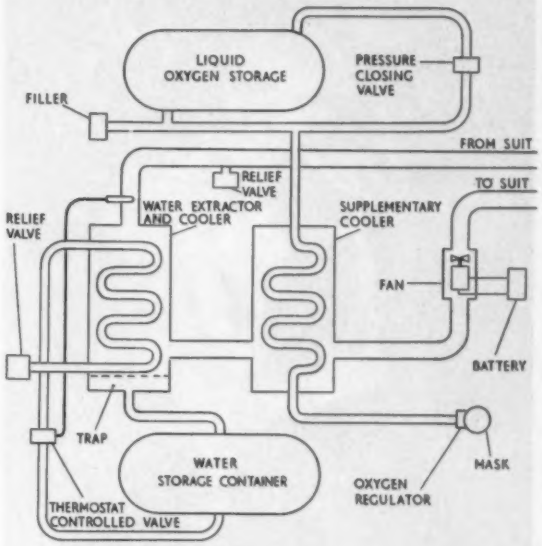


Fig. 39. Water evaporation system for lunar suit.

Emergencies

There are a number of emergency conditions which may arise and for which provision should be made. They include: emergency escape during take-off or re-entry, fire hazard in the space vehicles, and survival when alighting on water. These conditions and the measures that can be taken to counter them are described below.

EMERGENCY ESCAPE DURING TAKE-OFF OR RE-ENTRY

As already mentioned, the crew will wear their full pressure suits during both the ascent into orbit and the re-entry phase. In the event of failure of the pressure cabin or its main oxygen supply it is possible to pressurise the suit and to supply oxygen for breathing by means of a self-contained oxygen system. Fig. 41 shows a demand emergency oxygen regulator of the type at present being supplied for military aircraft, the entire system being attached to the ejection seat, quite independent of the main supply.

On operating the associated cylinder-release mechanism, the emergency oxygen supply immediately pressurises the suit, within a specified time, and provides the oxygen for breathing in accordance with the demands of the user. The regulator maintains in the suit a pressure of 2·7 lb./sq. in. abs. at altitudes above 40,000 ft.

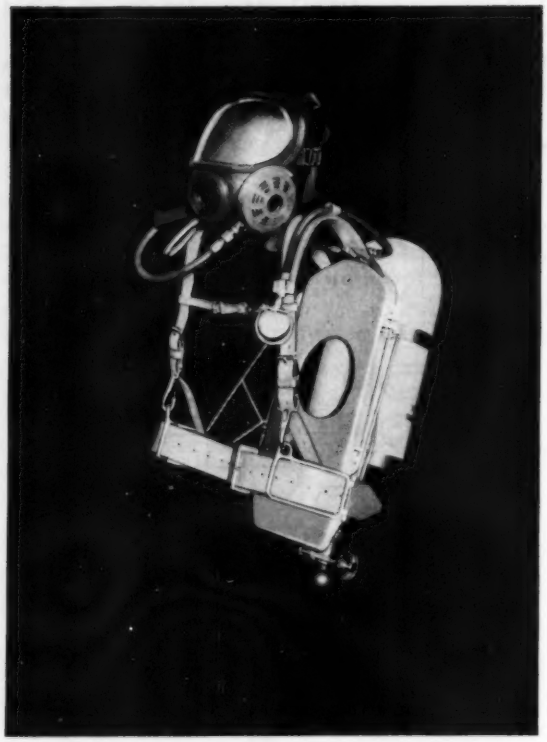


Fig. 40. Normalair compressed air breathing set.

FIRE HAZARD IN THE SPACE VEHICLES

As in an aircraft, fire will be a serious hazard in a space vehicle due to the extensive electrical circuitry. After a fire in a nuclear submarine recently, it was appreciated that it was not only necessary to supply conditioned air for normal breathing, but that breathing sets for fire-fighting purposes, enabling the crew members to be independent of the surrounding atmosphere, were also required.

Equipment for this purpose is shown in Fig. 40. Alternatively, a set similar to the one illustrated can be used in conjunction with a remote bottle supply. Compressed air at 2,000 or 3,000 lb./sq. in. is used to give reasonable endurance, or the air can be supplied from the main provisioning equipment by a long hose.

ALIGHTING ON WATER

It is assumed that in an emergency, the crew compartment may be ejected from the re-entry vehicle and come down on water. The crew must, therefore, be provided with a dinghy as mentioned in a recent press release of the Mercury project.[7] An artist's impression of a dinghy alongside a Mercury capsule is shown in Fig. 42. Food and water supplies are necessary for a

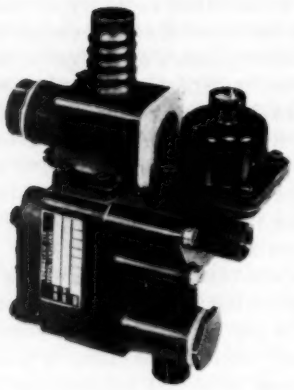


Fig. 41. Normalair Demand Emergency Oxygen Regulator.

number of days, and automatic inflation of the dinghy is also required. Suitable inflation equipment has already been produced, and the components of an aspirated inflation system are shown in Fig. 44.

The compressed air cylinder is of 250 cu. in. capacity, and is charged to 3,000 lb./sq. in.; the aspirator makes use of an air injector principle as shown in Fig. 43. A pull of 10 to 15 lb. on the operating cable causes a

Fig. 42. Dinghy alongside Mercury capsule.

break-off tube in the operating head to be sheared, allowing the cylinder to discharge. Approximately 80% of the air required to inflate the dinghy is taken from the surrounding atmosphere, the remaining 20% from the cylinder itself. This feature greatly reduces the installed weight of the system and also ensures a short inflation time.

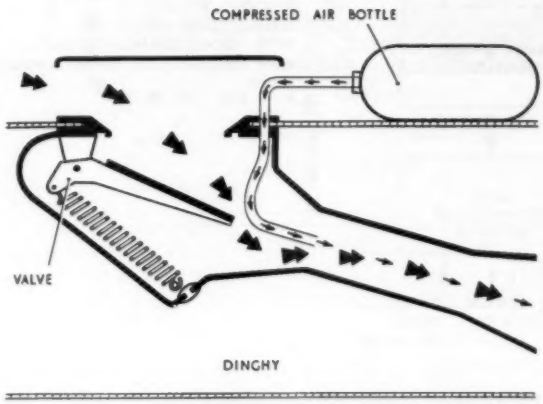


Fig. 43. Schematic diagram showing the operation of the aspirated inflation system.

Time for inflation of an 80 cu. ft. buoyancy chamber dinghy is only 10 seconds; the overall weight of the aspirated inflation system is 15½ lb., the aspirator being only 1 lb.

Fig. 44. Components of the aspirated inflation system.

These are only three of the many aspects of a 'fail safe' policy which must be covered. It is one thing to be able to show that a project is feasible assuming the engineering to be perfect all the time, but another to complete the undertaking satisfactorily when the laws of probability of component failure are taken into account. A venture to the Moon needs a very careful analysis of all the possible failure cases, as well as a great deal of development work, if such a journey is to succeed.

THE FUTURE

It has been shown that for the short duration of a few hours on the Moon, the environmental problem is well understood and should present no great difficulty. Similarly, for seven days' endurance in a space vehicle, a liquid oxygen system presents no insuperable weight problem.

A liquid oxygen system does, however, present quite a large weight penalty in a space station, even if a regenerative method of absorbing carbon dioxide is employed. The engineering details, for a six-month sojourn for 10 men, have already been described in this paper and it is obvious that as the duration becomes longer, so does the prospect of a more closed cycle ecology become more inviting. The first step would be the use of plants, especially some of the simpler types of algae, for removing carbon dioxide and supplying all or part of the oxygen.

Fig. 45 shows, in diagrammatic form, the typical conversions that take place in an ideal closed cycle so far as man is concerned and, rather surprisingly at first sight, it will be noticed that there is, in fact, a nett *output* of oxygen. This is because the 1 lb. of dehydrated food per day shown as the sole nett intake is composed partly of fats and partly of hydrocarbons, the hydrogen of which is burnt to water. In the diagram, this is shown further broken down into its constituent elements. The only function of a man's food intake is to liberate energy and to provide material to replace that lost by wear and tear, as, of course, his weight fluctuates only slightly in a given time. The discussion

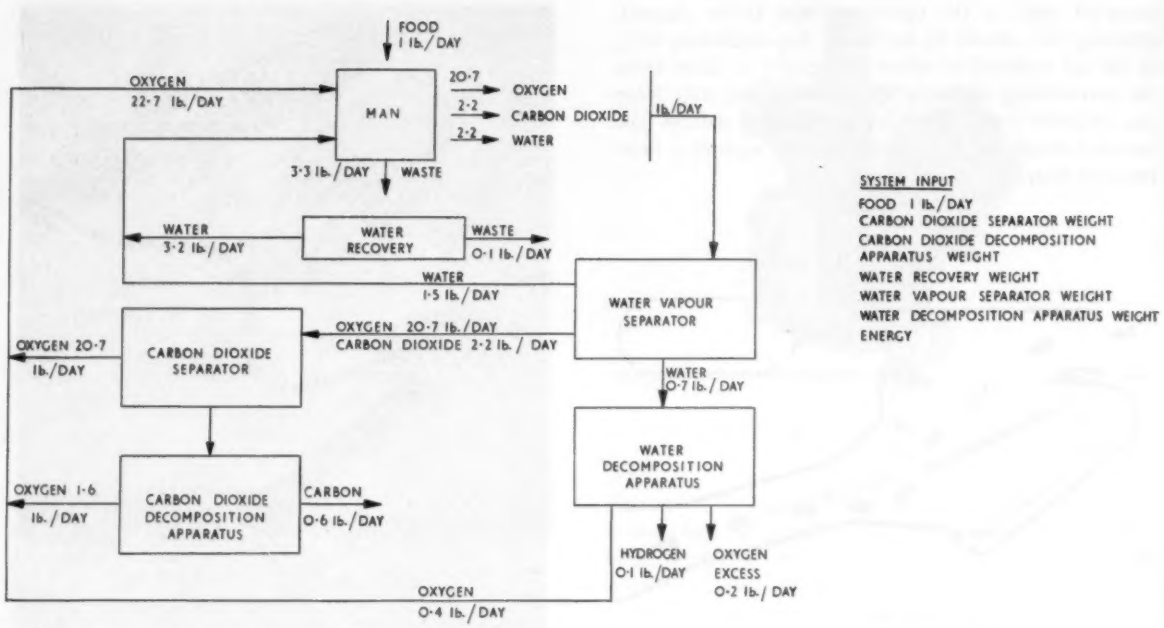


Fig. 45. Diagram of an ideal closed cycle system showing nett intakes and outputs of a man.
(By courtesy of R. W. Roundy and D. A. Keating, Wright Air Development Center, U.S.A.)

in this paragraph does not, however, invalidate the statement given earlier that the nett requirements of a man comprise certain quantities of food, oxygen, and water; the statement here covers purely the nett amount to be added to, and subtracted from, a man's otherwise closed cycle to make it work.

Whilst ultimately we might hope to create a perfectly closed system using plants, i.e. one in which there is no overall weight variation and only the energy of sunlight is provided from the outside, the first stage is to arrange a system whereby the plants are used only for gas exchange. Even this could represent a useful saving in weight.

A number of experiments are in progress throughout the world covering the development of algae systems, one of these being at the Bendix Aviation Corporation in America.[19] Firstly, a number of mice were kept alive in a closed environment for periods up to three weeks, and now work is proceeding with a man-sustaining system. See Fig. 46.

The algae used are of the species Anicystis Niculans, and for sustaining two mice of total weight 66 grms., 11 grms. of dry algae in one gallon of water were used, the tank being brightly illuminated by circular fluorescent lamps placed around it. Other experimenters have found that an economic proportion for algae is one part by weight to 100 parts of water.

It appears that one great problem is to supply a sufficient intensity of light to as great a proportion of the algae as possible, for photosynthesis to take place. Natural or artificial light may be used, and in the Bendix

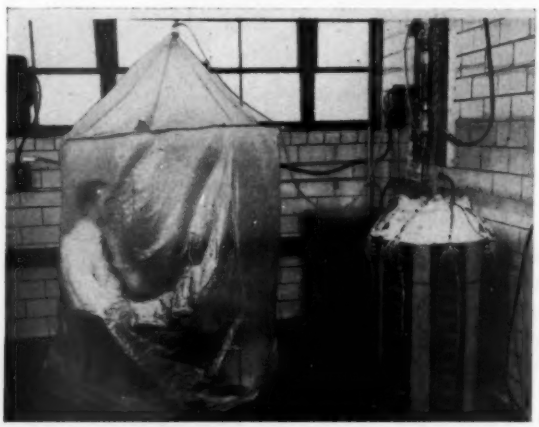


Fig. 46. A man-sustaining closed-cycle experiment.
(By courtesy of the Bendix Aviation Corporation of America)

man-sustaining experiments 30-watt fluorescent lamps were actually immersed vertically in the algae-bearing liquid. These also served to keep the temperature up to 106°F, that being the optimum for the algae used.

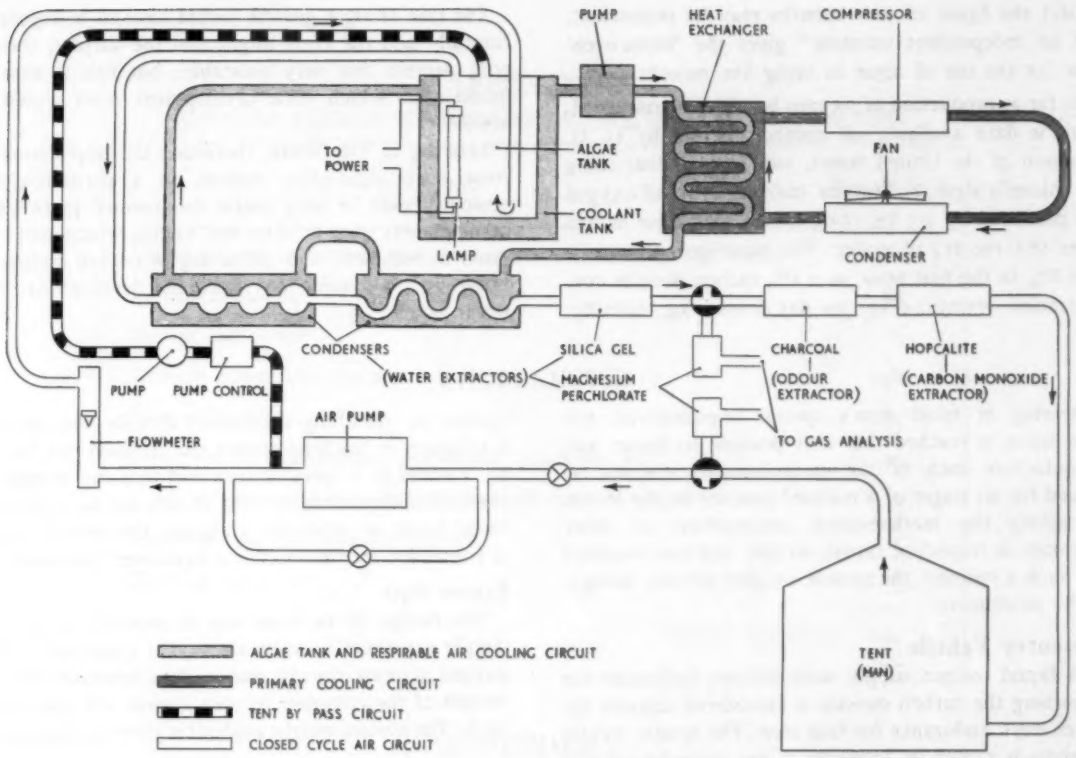


Fig. 47. Schematic arrangement of the man-sustaining closed-cycle system.

It appears that 81 of these tubular lamps are required in a 30-gallon drum of algae-bearing solution for sustaining one man, or to be more precise for the removal of his carbon dioxide, since for this series of experiments data is available only on the amount of this gas absorbed, and not for the amount of oxygen liberated. Nearly 2½ kw. of heat is given off by these lamps, and thus a cooling circuit is also provided. It should be stressed that this experimental work does not necessarily demonstrate just how a system designed for a space station might appear. In particular, one would hope to be able to use the Sun's light rather than have to make use of artificial illumination, which is produced at very low efficiencies.

The large number of lamps used in the Bendix test-rig is necessary because at a depth of 0·6 cm. below the surface of the algae-bearing liquid 95% of the light intensity has already been absorbed. Since 500 candle power is a suitable intensity for activating the algae, the method adopted is used to keep the solution in thin layers close to the light source. Air with a relatively high concentration of carbon dioxide is bubbled up between the lamps, the algae consuming a fraction of the gas en route, and liberating oxygen.

The Hopcalite container shown in the Bendix circuit diagram is for the extraction of carbon monoxide; according to some authorities this toxic gas is given off by algae in very small quantities, and in any case it is also given off by man, to the extent of some 10 c.c.'s per day.[15]

Preliminary conclusions would indicate that a period of at least nine months is required before the tank containing algae would show a weight advantage over the appropriate quantity of lithium hydroxide, both continually absorbing the carbon dioxide from a man.

Such a comparison, on a direct weight basis, takes no account of any electrical power that might be required for the algae illumination, or for cooling the algae tank; nor does it reckon with the weight or power required, in either system, for air circulation through the carbon dioxide extraction equipment, and water vapour and odour-removing units. No credit has been given for the algae replenishing the air with oxygen, though this would undoubtedly take place; thus in this

respect the figure of nine months may be pessimistic, and an independent estimate[20] gives the 'break-even' time for the use of algae as being five months.

So far as production of oxygen by algae is concerned, there is data available on another species by H. G. Clamann of the United States, who states[20] that using the chlorella algae, 25 litres/hr. (0·0745 lb./hr.) of oxygen are produced by 2·3 kg. (5·05 lb.) of wet algae in 230 litres (8·1 cu. ft.) of water. The plant growth rate is 4 to 8% in the first hour, at a 1% carbon dioxide concentration, giving 2·6 kg. per day from 1 kg., initially.

The rate of algae growth would have to be regulated carefully and the crew might find the surplus, though 50% protein, not very palatable; but this is another problem on which some development work would be needed.

Looking to the future, therefore, the application of some such algae-using system, in a partially-closed ecology, could be very useful for manned journeys to other planets such as Mars and Venus, which will take years to complete, and the saving in overall weight by using such a system may make its development well worth while.

CONCLUSIONS

Bearing in mind man's special requirements, the conclusion is reached that it is possible to design and manufacture each of the environmental systems required for all stages of a manned journey to the Moon. Accepting the mathematical assumptions of other scientists in respect of thrust, weight, and time required for such a journey, the system weights are not thought to be prohibitive.

Re-entry Vehicle

A liquid oxygen supply with lithium hydroxide for absorbing the carbon dioxide is considered suitable for seven days' endurance for four men. The system weight analysis is shown in Appendix 1, but these figures will be very much dependent on the electrical equipment assumed and hence on the energy to be removed.

Space Station

It is clear that the weight of the oxygen needed for the period envisaged is not impracticable when compared to the total weight of the space station. However, since the placing of unnecessary weight in orbit is to be avoided, it is highly desirable to use a reversible system for absorbing the carbon dioxide and rejecting it to space. It has been shown that 10 men can live for six months in a space station and that the weights of the environmental equipment should not be more than those listed in Appendix 2. Again, the overall weight is controlled by the electrical equipment assumed.

Lunar Suit

The design of the lunar suit is shown to be a fairly simple extension of suits already in existence, and of oxygen systems already proven. It is estimated that the weight of the complete oxygen system will not exceed 40 lb. The system weight analysis is given in Appendix 3.

It is thus possible to conclude that although the application of existing knowledge should enable a man to live during all stages of a journey to the Moon, as well as on the Moon itself, the indications are that for journeys to other planets such as Mars or Venus, which are at present estimated to take several years, a modified closed-circuit ecology using algae will probably be necessary.

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Equipment mentioned in this paper is covered by British and Foreign Patents.

APPENDIX 1

RE-ENTRY VEHICLE ENVIRONMENTAL SYSTEM WEIGHT ANALYSIS

Item	Weight (lb.)
Liquid oxygen converters with evaporator coils and control valves	300
Pressure suits	60
Blower and motor	2
Lithium hydroxide canisters	158
Heat exchanger	15
Freon system (compressor, evaporator, condenser, etc.)	40
Cabin pressure regulator and temperature control system	5
Charcoal and Hopcalite containers	5
Ducting, valves, etc.	5
TOTAL (approx.):	600 lb.

APPENDIX 2

SPACE STATION ENVIRONMENTAL SYSTEM WEIGHT ANALYSIS

Item	Weight (lb.)
5 Liquid oxygen converters with evaporator coils and control valves	13,850
23 Cabin pressure regulators	46
5 Blowers and motors	5
10 Skin heat exchangers (extra to material of skin of vehicle) and valves	400
10 Zeolite canisters and valves	410
10 Solar mirrors and actuating equipment	200
5 Charcoal and Hopcalite canisters	100
1,000 ft. Ducting and 92 shut-off valves	156
23 Circulation fans	23
Monitoring equipment and automatic valve systems, etc.	100
TOTAL (approx.):	15,300 lb.

APPENDIX 3

LUNAR SUIT ENVIRONMENTAL SYSTEM WEIGHT ANALYSIS

Item	Dead Weight (lb.)	Consumable Weight (lb.)
Oxygen storage container and valves	7½	
Water storage container	1½	
Cooler/water extractor	3½	
Supplementary cooler	1½	
Temperature and pressure control valves	1½	
Circulation fan and motor	4	
Battery	4	
Carrying frame and miscellaneous items	5	
Total:	28½	
Oxygen		8½
Water		3
Total:		11½
GRAND TOTAL:	40 lb.	

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